FOI-S--0220--SE

INTERNATIONAL ENERGY AGENCY

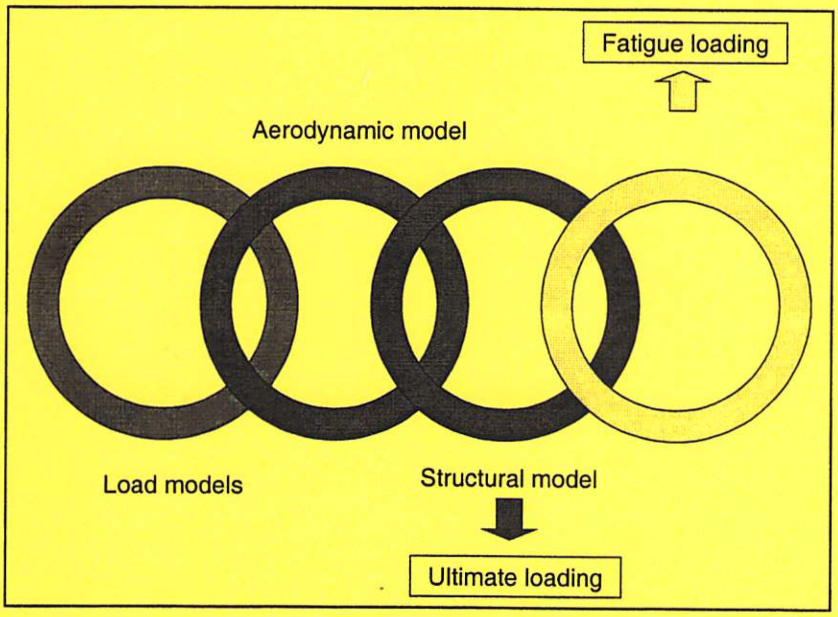
Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems
ANNEX XI

37th IEA Topical Expert Meeting

Structural Reliability of Wind Turbines

Roskilde, November 2001

Organised by: Risoe



FOI
SWEDISH DEFENCE RESEARCH AGENCY

Scientific Co-ordination:

Sven-Erik Thor
FOI, Aeronautics Division - FFA, 172 90 Stockholm, Sweden

CONTENTS

Structural reliability of wind turbines

IEA Symposium on Structural Reliability of Wind Turbines

INTRODUCTORY NOTE

by

Gunner Larsen, Risø

Wind energy is presently the most mature of existing alternative energy sources, and it is approaching the state where the production costs are competitive to traditional energy sources. This is the result of an impressive development during the past 20 years, and all prognoses indicate that this development will continue and probably even accelerate the coming years as a result of increasing international focus on environmental concern. A key explanation for this success is the continuous refinements and improvements of the wind turbine structures.

Modern wind turbines are complicated, time-varying dynamic systems made of advanced materials. The time dependence of the system dynamics is caused by the rotation of the rotor and possibly, in addition, by an active control strategy such as pitch regulation or active stall regulation. The wind turbine is exposed to deterministic as well a stochastic loading. Traditionally, the mean wind field in the short term, such as within 10-minute periods, and also gravity give rise to loads, which are modelled as deterministic loads. The turbulence of the wind and, for offshore turbines, the waves give rise to loads, which are modelled as stochastic. Also the mean wind field in the long term is of a stochastic nature.

In the design of wind turbine structures, ultimate loading as well as fatigue loading is addressed. The design process involves aeroelastic modelling of the wind turbine as well as specification of appropriate load scenarios. In addition to uncertainties associated with load and resistance, both the structural modelling and the load modelling may be encumbered with uncertainty. These uncertainties all have an impact on the safety against structural failure. The ultimate goal of the design procedure is to ensure an adequate safety against structural failure.

In this context, structural reliability analysis comes in handy as a rational method, within a probabilistic framework, to deal with the uncertainties involved in the analysis of the wind turbine structure performed in the design process. It encompasses in principle the complete model process, ranging from problem formulation, numerical discretisation, material specifications and loading conditions. The benefit of such an analysis is to ensure a suitable, a priori defined, low probability of failure for the structure in question.

Traditionally the involved uncertainties can be categorised into different disjoint classes:

- *Natural variability*. This is also known as inherent uncertainty. This is uncertainty associated with a random character inherent in the physics of a system. Related to wind turbine design, straight forward examples are stochastic wind loading caused by turbulence and stochastic wave loading, which both vary with time, and variability in material resistance, e.g. from point to point within a material volume. Natural variability is a type of uncertainty, which cannot be reduced.

- *Model uncertainty*. This class of uncertainties relates to the choice of deterministic as well as stochastic models applied in the design computations. Generally speaking, the model uncertainty is caused by insufficient knowledge/ability or selected simplifications in the mathematical formulation of the structural system. The model specification is a crucial step that might be responsible for a substantial amount of uncertainty – for example the well known "tail sensitivity" of reliability computations. Other examples would be the choice of an appropriate kinematic theory, selection of a suitable beam theory (Bernoulli, Timoshenko or more general beam theories including warping) and the selection of an appropriate fatigue evaluation model. Model uncertainty can be reduced by using a better model.

- *Statistical uncertainty.* Statistical uncertainty is closely associated with a limited amount of available data. It manifests itself as uncertainties in the relevant parameter estimates – f. ex. uncertainties in the estimated distribution parameters related to the probabilistic representation of the material resistance. Statistical uncertainty can be reduced by increasing the amount of data, e.g., by further sampling.

Structural reliability analysis constitutes the synthesis of the above listed sources of uncertainty into a measure of the probability of survival for the structure, and such analyses can further be condensed into structural design codes by so called partial safety factor calibration. Having calibrated the partial safety factors implies that the design cycle can be carried out in a conventional deterministic framework. The partial safety factors will then assure that the required low probability of failure is achieved, or that the deviations from this required probability are minimised.

The application of structural reliability methods are fairly new within aeroelastic design procedures for wind turbines, and this symposium is the first with this theme within IEA Annex XI. The theme for the symposium should be interpreted as structural reliability in a broad sense, and besides qualitative and quantitative modelling of types of the uncertainties described above, it also includes the synthesis of these terms into complete reliability analysis cycles and successive calibration of partial safety factors. Relevant modes of failure – or limit states – in this context are fatigue failure and failure in ultimate loading. Multiple failure modes or failures of several structural components may have to be combined for evaluation of the system reliability for a wind turbine.

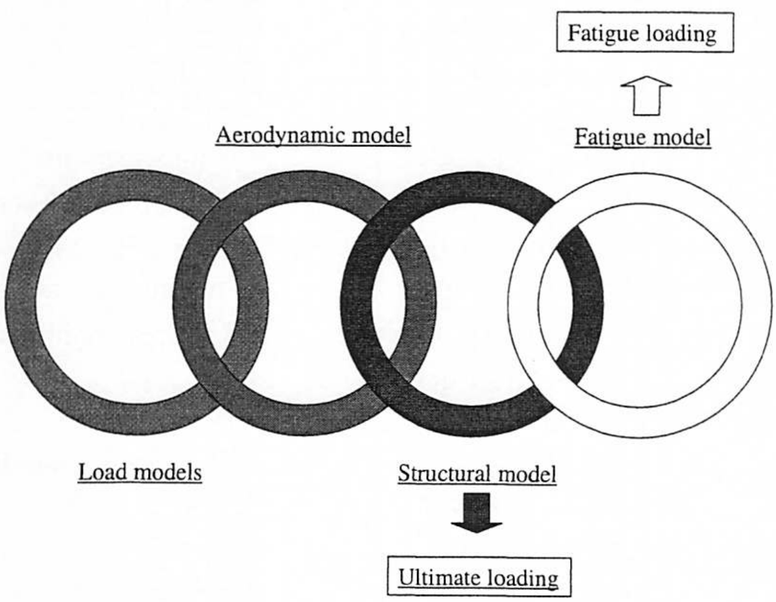
As a source of inspiration a list of potential topics is added below:

- Extreme wind conditions
- Gusts
- Wave- and ice loads
- Combinations of natural loads
- Uncertainty on load calculations
- Distribution of yaw errors
- Estimation of extreme loads
- Material resistance and fatigue models
- Limit states
- Calibration of partial safety factors
- Statistics of emergency events

Structural Reliability of Wind Turbines

Gunner Larsen
Wind Energy Department, Risø

Design of Wind Turbines



Load models

- "Series" of stationary load processes
  - Mean wind climate
  - Tower shadow
  - Shear/inflow
  - Turbulence
  - Extreme wind load situations
  - Wave loading
- Non-stationary load process
  - Wind loading
  - Wave loading

Uncertainties

- Model
  - Stationary/non-stationary?
  - Wind climate: Weibull?
  - Tower shadow: Potential?, Source/drain?, CFD?
  - Shear/inflow: Logarithmic?
  - Turbulence: Spectrum?, coherence?
  - Extreme wind load: Deterministic/stochastic?, coherent?, types?, shape?
  - Wave: Spectrum
- Parameter
  - Number of bins?
  - Weibull parameters?
  - Char. diameter?, source strength/geometry?
  - Surface roughness?
  - TI?, L?
  - Decay factor?
  - Time scale?, amplitude?
  - H_S, T_P

Aerodynamic model

- Blade element model [BEM] (stationary, laminar flow) + Prandtl's tip loss factor
- Stall model
- Actuator disc models (non-stationary, "communication" across stream tubes)
- Lifting line theory (load ★ vortex, wake)
- Panel methods (chord wise load ★ vortices, wake)
- Full CFD
- Aeroloads in deformed/undeformed configurations

Uncertainties

- Model
  - BEM?
  - Beddoes/Øye/... ?
  - Actuator disc?
  - Lifting line?
  - Panel method?
  - CFD?
  - Deformed/non-deformed configuration?
- Parameters
  - C_L?, C_D?, C_M?
  - Stall parameters?
  - C_L?, C_D?, C_M?
  - Vortex strength ϑ(r)?
  - ϑ_i(r)?
  - Turbulence closure model/direct numerical simulation?

Structural Model

- Beam model (small deformations/rotations)
- Beam model (large deformations)
- Shell model (small deformations)
- Shell model (large deformations)
- Solid model (small deformations)
- Solid model (large deformations)
- Control system
- Generator model

Uncertainties

- Model:
  - Beam model/shell model/solid model?
  - Small deformations/ large deformations?
  - Discretization in space and time?
  - Generator interaction with grid?
- Parameters:
  - Shear centre?
  - Elastic centre?
  - Stiffness properties?
  - Structural damping?
  - Mass distribution?
  - Laminate lay-up in production?
  - Backlash in gear wheels?
  - Generator characteristics?
  - Gear box losses?

Ultimate loading - uncertainties

- Uni-axial stress failure criteria?
- Multi-axial stress failure criteria?
- Natural/statistic variability in the material properties

Fatigue model

- Fracture mechanics approach
- Palmgren-Miner approach

Uncertainties

- Model:
  - F-M approach?
  - P-M approach?
- "Parameters":
  - Initial conditions (distribution of micro cracks)?
  - Natural variability introduced by the stochastic ordering of load cycles
  - Load cycle counting algorithm?
  - Variability in Wöhler parameters

Categorisation of uncertainties

- Natural variability (irreducible):
  - Uncertainty associated with a random character inherent in the physics of a system
- Statistical uncertainty (reducible):
  - Uncertainties in parameter estimates originating from limited amount of available data
- Model uncertainty (reducible):
  - Uncertainties related to the *choice* of models (idealisations, insufficient knowledge)

Reliability analysis

- Measure of probability of survival based on:
  - Quantification of uncertainties (distributions, ...)
  - Synthesis of all listed sources of uncertainty (Monte Carlo simulation, ...)

Partial safety factors

- Based on:
  - Reliability analysis
  - Selected acceptable failure probability
- Allow for:
  - Design cycle performed in traditional deterministic framework (⬇ efficiency!)
- Assure that:
  - Required acceptable (low) probability of failure is achieved on a rational basis

STRUCTURAL RELIABILITY AND DESIGN METHODS

Luc Rademakers[1]), Henk Braam[2])

ECN Wind Energy, P.O. Box 1, 1755 ZG Petten, The Netherlands, fax +31 224 56 8214

[1]) tel.: +31 224 56 4943; e-mail: rademakers@ecn.nl

[2]) tel.: +31 224 56 4657, e-mail: braam@ecn.nl

Introduction

Although it seems to be a deterministic approach, a first start to introduce structural reliability methods in the design process has been made in design codes by prescribing partial safety factors, which have been calibrated by means of structural reliability analyses. Such a calibration is by no means a trivial task and structural reliability methods form the formal and rational basis for this. The application of probabilistic methods for partial safety factor calibration is fairly new within the wind industry, but the support for this approach is growing.

Probabilistic techniques are used in the latest version of IEC 61400-1. To further introduce structural reliability methods in the design procedures of wind turbines, two separate, but closely related routes should be developed. Probabilistic design methods possibly with accompanying computer programs should be made available for manufacturers of wind turbines and suppliers of wind turbine components, such as blades and support structures. At the same time design codes should be adjusted in the way that target values for reliability should be included as well as the conventional partial safety factors for a traditional deterministic design approach. In this way a designer can consider to apply the sophisticated approach by using probabilistic methods, with the intention to manufacture his components more economically.

To support this process ECN has co-ordinated and participated in a number of EC-funded Joule projects dealing with structural reliability of wind turbine blades. In the Joule III project Prodeto the fatigue loading of wind turbine blades was considered and a method for the calibration of the safety factors developed by DNV and Risø, was demonstrated. In the Joule III project Profar the scatter in fatigue strength of blades was considered. As outlined below it appeared from these projects that it is very difficult to develop at this moment probabilistic design methods for blade manufacturers. For this reason and because of the involvement in offshore wind energy the new initiatives at ECN aim at the support structure of offshore wind turbines. In this paper the motives to apply probabilistic methods for the support structure are presented and the approach of the future research is outlined.

Blade Design

In the period 1996 – 1998 ECN Wind Energy has co-ordinated and participated in the JOULE III project Prodeto [1, 2]. One of the main objectives of this project was the 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 safety factors calibration tool. The implementation of the computer code was mainly based on the procedures developed within the Joule II project: EWTS I, subproject 'Calibration of Safety factors' and on research carried out by DNV and Risø [3, 4]. The code can be applied to analyse the fatigue failure of blades only and is able to handle both measured and calculated 10-minutes time series. With this program a case study has been carried out for two Micon M1500-60/150 kW turbines, one located in The Netherlands and one located in Denmark. Both measured and calculated 10-minute time series have been considered, and a first order reliability analysis of the blade against failure in flapwise bending was carried out. It was demonstrated that the calibration of partial safety factors can be done on the basis of structural reliability methods, although the following problems were foreseen at the end of the project:

- Only a suitable model for fatigue failure of rotor blades in flapwise direction was available for the Prodeto project. Models for fatigue in edgewise direction and other failure modes should be developed and verified.
- Design codes are valid for different wind turbines located at several locations, so the wind climate can be different. This implies that the partial safety factors to be used in a design code should comprise a great variety of situations. So to the calibration of the partial safety factors should be based on a large amount of time-series for different turbines at several locations.
- Besides uncertainty in the observed loads and the inherent scatter in the material fatigue properties, the following effects are covered by partial safety factors in existing codes and should be taken into account:
    - wear of materials;
    - variability in fabrication methods;
    - size effects;
    - uncertainty in load measurements;
    - uncertainty in wind climate determination/site parameters.

Nevertheless the calibration of partial safety factors by means of structural reliability methods is seen as an extremely suitable method to be used for the determination of the partial safety coefficients in design codes. However, due to the enormous amount of data which should be evaluated for this purpose an international co-operation is required.

The results of the Prodeto project show that the calibaration of partial safety factors can be handled, and is expected to be of significant benefit for the wind turbine industry and for certifying bodies.

However, the project did not succeed in developing a design tool. Based on the experience obtained in the Prodeto project it is expected that the objective to develop a probabilistic design code, which can be used by blade manufacturers in the regular design process is too ambitious at this moment, among others for the following reasons:

- The loading of the blades has to be characterised by the local stresses, which is complex due to the non-linear aero-elastic behaviour.
- The various limit state functions are complex due to multi-axial stress states and the different failure mechanisms (fatigue in the parent material, debonding, delamination, buckling, etc.)
- Composite materials show a very complex material behaviour;
- Application of structural reliability methods requires specific knowledge, which is not in general available in the industry.

At that time no relation between coupon test data and the actual failure of the blade was available. For the case study material properties obtained from coupon test were used straightforward to characterise the strength of the blades. It appeared that inherent variability in the material data is the most important source of uncertainty. So the strength in the structural reliability model need more attention. Both the inherent scatter in fatigue strength and the relation with coupon data need to be considered in more detail, which has been done in the Joule III project Profar, which is in the stage of completion at the moment [5-7].

Within this project 42 small rotor blades have been tested in static and fatigue. Next to these blades, a total number of 35 coupons of identical material as that of the blades has been tested statically and under fatigue loading. The tests served two main purposes, finding the scatter in the blade properties and relating the coupon test data to actual failure of the real blade. In order to serve these purposes two different sets of tests were done. One set aimed at failure in the prismatic outboard section of the blade in the parent glass fibre material, while the other aimed at failure in the geometrically complicated root section of the blade where failure of the bonding line, collapse of the spar or other mechanisms can be observed. These latter tests were done both in edgewise and in flapwise direction. The tests have been performed at three laboratories, the Stevin laboratory of the Technical University of Delft, The Netherlands; the test facilities of the Centre for Renewable Energy Studies, CRES in Pikermy, Greece; and a test facility at Risø National Laboratory, Roskilde, Denmark.

The results of the coupon tests are represented in Figure 1. The results for the prismatic tip section tests for the three laboratories are represented in Figure 2. In Figure 3 the results for the root section flapwise tests are represented and in Figure 4 the results for the root section edgewise tests are represented.

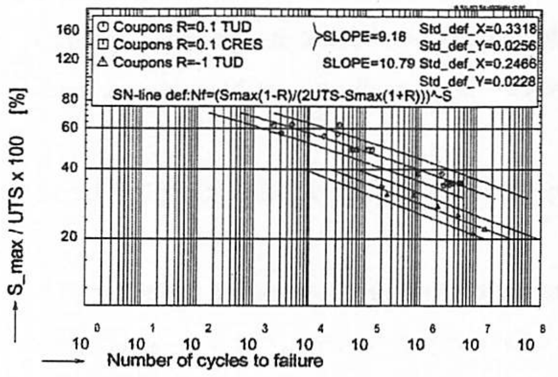


Figure 1: Cycles to failure for the coupon tests.

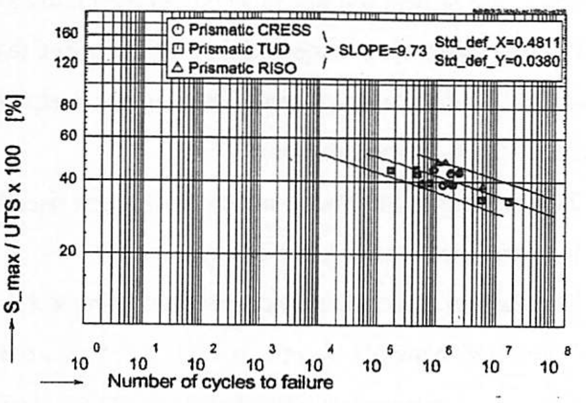


Figure 2: Results for the tip section tests.

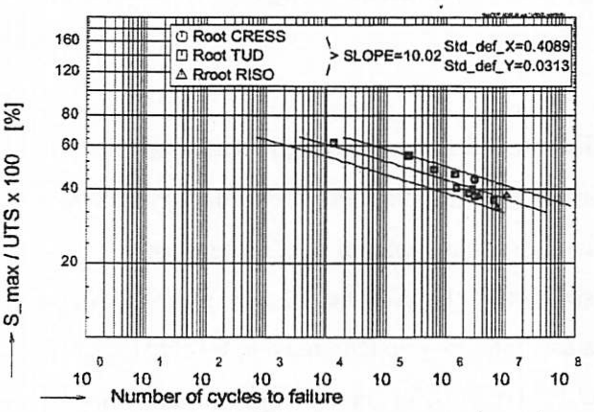


Figure 3: Results for the root section flapwise tests.

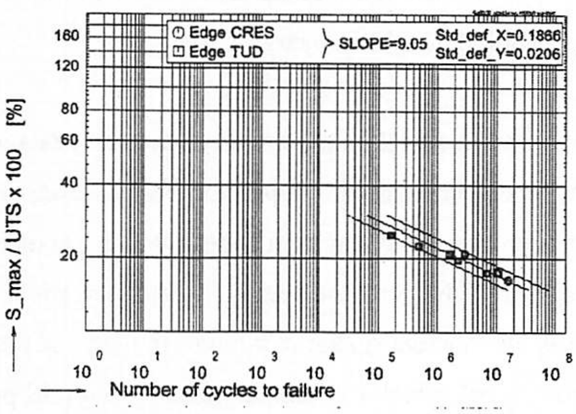


Figure 4: Results for root section edgewise tests.

The fitting of the blade and coupon test data to a Goodman relation gave slopes close to 10. Hence the adopted fatigue formulation fits good with blade- and coupon test results and describes the influence of the stress ratio very well. Not only the slope but also the failure stress level of coupons and blades are in the same range.

So the strength distribution of the parent blade material can be well described by coupon tests. Remarkable is the agreement between coupon data and blade data for the root section, as in the root section different failure mechanism were observed (fatigue of parent material, failure of the bonding line and failure of the spar). As it is not clear whether this agreement is accidental more research into failures of the root section is required. Unfortunately this could not be done within the Profar project.

Support structure

In contrary to blade design it is expected that probabilistic design methods can be introduced for the support structure of offshore wind turbines more easily for two reasons.

1. The need for probabilistic design techniques is more urgent. The investment costs of the support structure are significant, while these costs are more or less directly related to the structural design. The design has to deal with the simultaneous action of the loads induced by wind, waves and current, which all have a random nature. In a conventional deterministic design approach these

loads would be treated independently and combined in a conservative way, for instance by adding the severest loads due to wind, waves and current linearly. So it is assumed that the severest loads due to wind, waves and current do occur at the same time and work in the same direction. Applying structural reliability methods take into account the correlation between the external loads, which generally will result in much lower design loads and consequently the investment costs can be reduced significantly.

2. The application of probabilistic design methods is well known in offshore engineering, and the offshore companies will also be involved in the design and manufacturing of the support structures for wind turbines. Furthermore a number of problems experienced in the probabilistic approach for the design of blades are less pronounced for the support structure, such as:
   - The modelling of the structural behaviour of the support structure as compared to the high non-linear aero-elastic models for blades, as the loads have to be characterised in terms of local stresses or strains;
   - The strength is determined by the material behaviour and the failure modes, which are much better understood for steel than for composites. Furthermore both for steel and for concrete a lot of knowledge and information is probably available from the offshore industry.

To further introduce probabilistic design methods in the field of wind energy ECN Wind Energy has initiated new activities, but now aimed at the support structure. To demonstrate the profits of applying probabilistic techniques and to get a deeper understanding of the problems a designer might experience, a case study will be carried out. As part of this case study 2 or 3 representative designs of a support structure will be analysed both in the conventional way and by means of structural reliability methods. The following failure modes will be considered:

- Fatigue;
- Extreme loads during operation;
- Extreme storm.

For the determination of the loads use will be made of the computer program PHATAS for analyses in the time domain and of the computer program TURBU-offshore for analyses in the frequency domain. TURBU-offshore is under development at the moment. The existing program TURBU will be adjusted for offshore applications; wave loading and the behaviour of the foundation will be included. TURBU provides the possibility to perform analyses in the frequency domain, hence stochastic loads can be used as input and a link with a structural reliability approach seems to be possible. Central part of the TURBU model and computer program is the linearisation of the model in several working points.

Concluding Remarks

The use of probabilistic methods in design codes is fairly new for the wind industry. The activities in this field originate from the blade design and a number of research projects have been carried out or are ongoing. It appears that the procedure for calibration safety factors is well understood, although for practical application a number of serious problems still have to be solved, such as the development of validated failure models, and the handling of a large amount of time series. As we have to deal with inherent uncertainties it is very important that this research is continued, since the calibration of safety factors based on structural reliability provides a solution to handle these uncertainties in a rational manner.

The development and use of probabilistic design tools requires that target values for reliability are specified in design codes. The development of a design tool for blade design seems to be very ambitious at this moment amongst others due to the complex failure mechanisms (fatigue, failure of the bonding line, buckling, failure of the spar etc.) in connection with the complex material behaviour of composite materials. For the support structure of offshore wind turbines the introduction of probabilistic design methods on the short term seems more promising. On the one hand the need is much higher due to high investment cost of the support structure. On the other hand the offshore industry already has become used to work with probablitic methods.

References

[1] H. Braam, C.J. Christensen, J.J.D. van Dam, G. Larsen, K.O. Ronold, M.L. Thøgersen, K. Argyriadis, J. de Boer, and O. Fabian, , *Probabilistic design tool Prodeto, Publishable final report EC Joule III project JOR3-CT95-0026*, ECN-C--99-023, May 1999.

[2] H. Braam, C.J. Christensen, K.O. Ronold, M.L. Thøgersen, *Prodeto, a computer code for probabilistic fatigue design*, Proc. European Wind Energy Conf. 1999, pp. 195- 198, 1999.

[3] K.O. Ronold, J. Wedel-Heinen, and C.J. Christensen, *Calibration of Partial Safety Factors for Design of Wind-Turbine Rotor Blades against Fatigue in Flapwise Bending*, 1996 European Union Wind Energy Conf., Goteborg, 1996.

[4] K.O. Ronold, J. Wedel-Heinen, and C.J. Christensen, *Reliability based fatigue design of wind turbine rotor blades*, Elsevier, Eng. Struc. 21, 1999, pp. 1101 – 1114.

[5] H. Braam et al., *Probability distribution of fatigue strength of rotor blades (Profar), publishable final report*, to be published as ECN report

[6] J. J. Heijdra et al, *Probability distribution of fatigue strength of rotor blades, Profar,* , Proc. European Wind Energy Conf. 2001.

[7] H. Van Leeuwen et al, *Probability distribution of fatigue strength of rotor blades, Profar,* to be presented at the ASME conference in Reno 2002.

Uncertainty in Design Loads

Gunner Larsen and
Anders Melchior Hansen
Wind Energy Department, Risø

Aim

- To quantify the magnitude of uncertainty associated with design loads as established based on traditional aeroelastic computations

Simplification

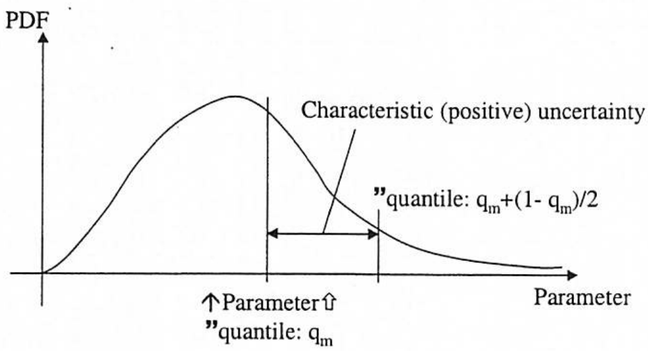
- Model uncertainty neglected
- Analysis restricted to fatigue loading
- Distributions of parameter uncertainty replaced by characteristic parameter uncertainty (based on PDF's)
- One modern wind turbine (Bonus 2MW) considered
- Selection of 3 characteristic (mean) wind regimes
- Design conditions as specified in IEC 64100-1

Load conditions

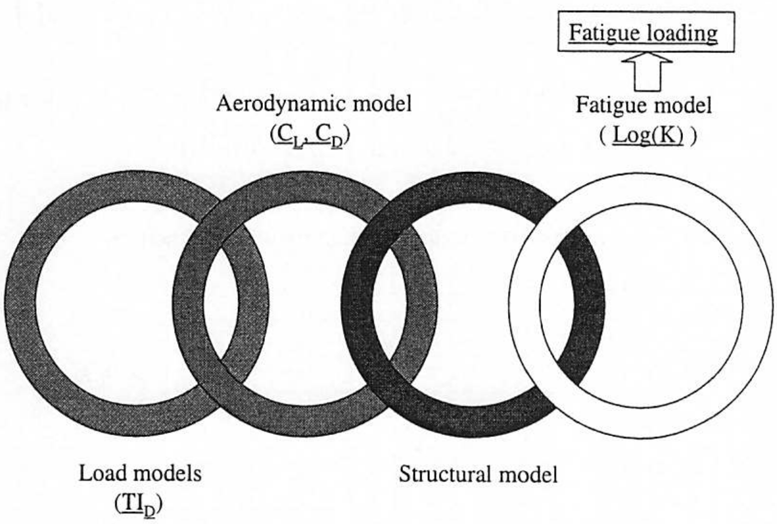
- IEC 61400-1; wind class I; turbulence class B
- 3 mean wind regimes (7.5m/s, 14.5m/s and 21.5m/s)
- Rayleigh distributed mean wind speed (corresponding to wind class I)

Characteristic Uncertainty

- Condensation of PDF in one number with correct magnitude
- Defined by the quantile that in average is exceeded with prob. 0.5 given a positive deviation from the mean value



Selection of vital model parameters

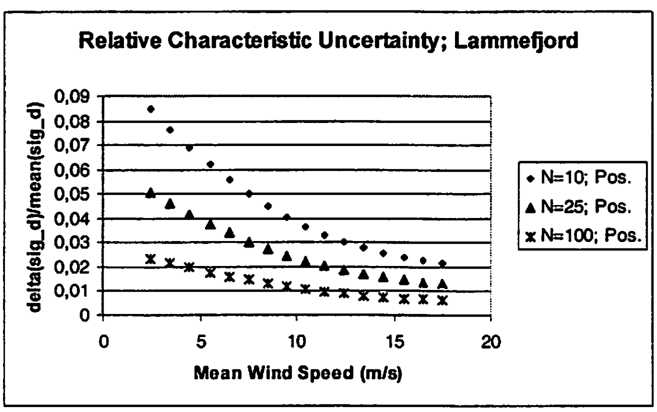


Design turbulence intensity (1)

- TI_D = ↑TI⇧ + ♋ ♦$_{TI}$
- Analytical model describing the statistical uncertainty on TI_D as function of sample size (N):
  - Log-Normal (TI) approximated by truncated Normal distribution
  - ⓤ ♦$_{TI}$ is Gamma distributed
  - ⓤ TI and ♦$_{TI}$ is statistical independent
  - Resulting distribution of TI_D obtained from a convolution of PDF (♦$_{TI}$) and CDF (↑TI⇧)

Design turbulence intensity (2)

- Population of TI and population of ♦$_{TI}$ depends on the mean wind speed (offshore/onshore)

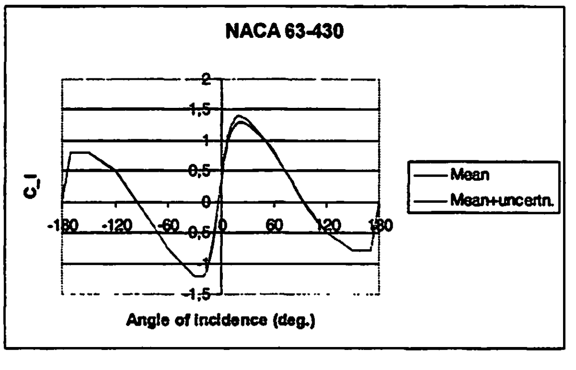


C_L and C_D (1)

- Distribution established based on:
  - Blind test among 4 specialists in aerodynamics
  - NACA 63-415, 63-418, 63-421, 63-424 and 63-430
  - Emphasis on angles of incidence corresponding to normal operation of the wind turbine
  - C_L, C_D assumed Normal distributed conditioned on the angle of attack

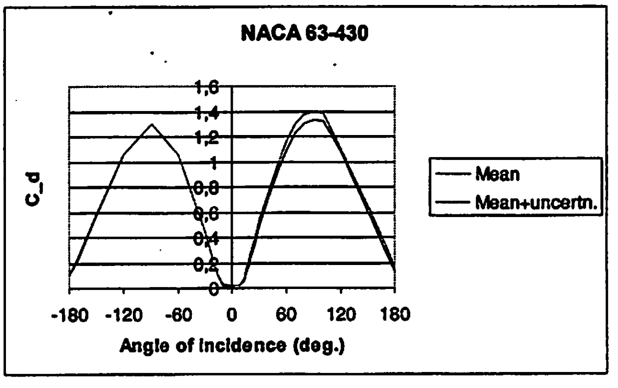
C_L and C_D (2)

- Characteristic uncertainties; C_L:

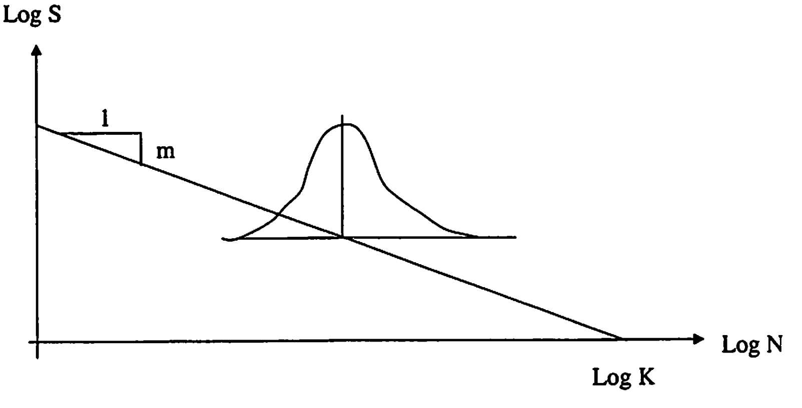


C_L and C_D (3)

- Characteristic uncertainties; C_D:



S-N curve (1)



S-N curve (2)

- Steel:
  - No statistical uncertainty on the Wöhler exponent
  - No statistical uncertainty on the intercept Log(K)
  - The S-N curve express expected value of Log(N) given Log(S) ⬇ natural variability about ↑ Log(N) ⇧
  - The variability of Log(K) is described as a Normal distribution with standard deviation 0.2.

S-N curve (3)

- Laminate:
  - Statistical uncertainty on the Wöhler exponent
  - Statistical uncertainty on the intercept Log(K)
  - The variability of Log(K) is described as a Normal distribution with standard deviation 0.4 (as based on Echtermayer data)

Fatigue analysis

- Based on Palmgren-Miner approach
- Load cycles identified by Rainflow counting
- Determination of equivalent moments for specified Wöhler exponents
- Uniaxial stress conditions assumed
- Determination of equivalent stresses in selected hot-spots
- Based on the S-N curves, the relative/normalised "consumption" of available fatigue resistance is determined and used as fatigue load measure

Simulation matrix

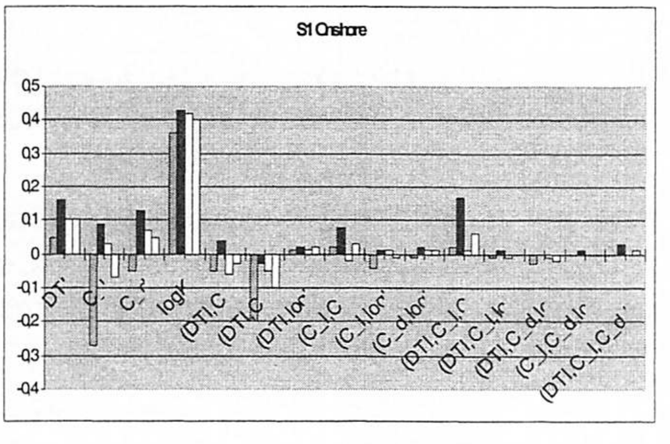
- 6 x 10 minutes to obtain convergence in fatigue

Simulation	TI	Cl	Cd	Log N
1	m	m	m	m
2	m	m	m	s
3	m	m	s	m
4	m	s	m	m
5	s	m	m	m
6	m	m	s	s
7	m	s	m	s
8	m	s	s	m
9	s	m	m	s
10	s	m	s	m
11	s	s	m	m
12	m	s	s	s
13	s	m	s	s
14	s	s	m	s
15	s	s	s	m
16	s	s	s	s

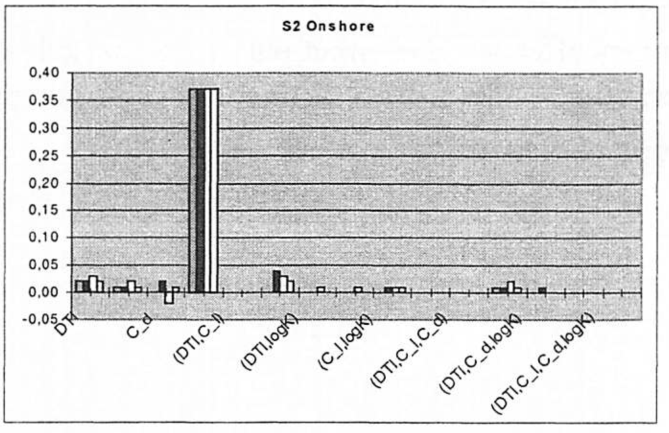
Synthesis

- 2-level factorial method
- Primary effects (ONE input parameter) based on averaging results from 8 different “expansion”points
- Coupling effects

Results (blade root; flap)



Results (blade root; edge)



Conclusions

- Uncertainty in the material (fatigue) properties is a dominating factor. However, as it is caused (mainly) by natural variability it can not be substantially reduced unless different materials are introduced
- Uncertainty in predicted lifetime caused by uncertainty in in TI_D, C_L and C_D is also significant - these can be reduced by increasing N and improving the methods for predicting the aerodynamics coefficients
- The *resulting* uncertainty is not additive in the selected uncertainty factors

Statistical Uncertainty in Design Turbulence Intensity - An Analytical Approximation

Gunner Larsen
Wind Energy Department, Risø

Design Turbulence Intensity (1)

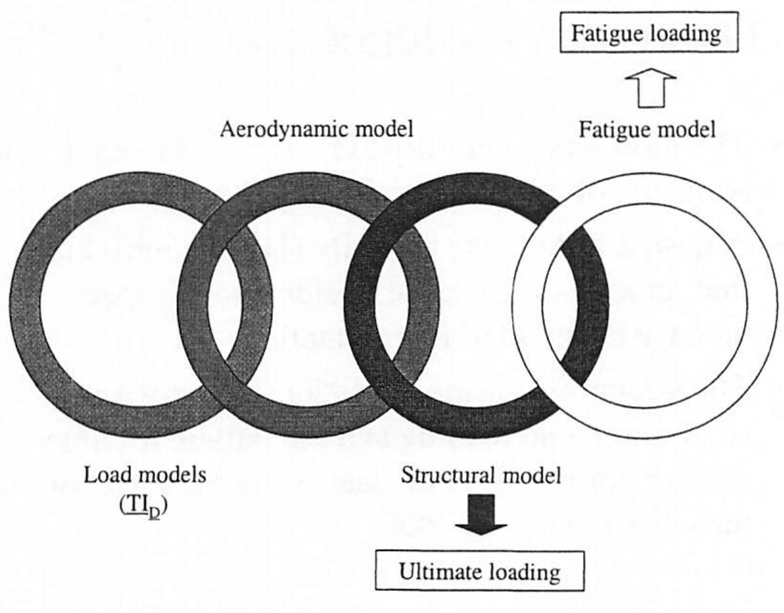
- The turbulence intensity (TI), at a given site, follow some distribution (natural variability)
- A design turbulence intensity (DTI) is introduced that, in an average sense, yields same fatigue damage as the PDF representation
- The strongly non-linear relationship between stochastic wind loading and the fatigue lifetime consumption ⇒ DTI deviates from the mean of the turbulence intensity PDF

Design Turbulence Intensity (2)

- The TI characteristics might depend on the mean wind speed
- The standard deviation of the wind speed standard deviation is an essential parameter
- The design standard deviation (and thus DTI) is often parameterized as

$$\sigma_{d,T}\left(U_T\right) = \overline{\sigma_T\left(U_T\right)} + C\sigma_{\sigma,T}\left(U_T\right) \quad ,$$

Design of Wind Turbines



Estimation of DTI (verification)

- Limited number of measurements
- Statistical uncertainty introduced that follow some PDF
- Determination of this PDF (conditioned on the mean wind speed), as function of a suitable selected statistical degree of freedom, is the aim of the presentation

Approximation

- The traditional Log-Normal distribution of (U_T) is replaced by a truncated Gaussian distribution
  - ⇐ the two quantities on the right hand side of the defining equation are statistical independent
- Thus:
  - evaluate the PDF separately for each of those
  - synthesise these into a PDF of the design turbulence standard deviation

Distribution of Mean TI

- Gaussian distribution with the lower tail truncated at zero
- Thus:

$$\overline{\Sigma_T} \in G_t\left(\mu_\sigma, \frac{\sigma_\sigma}{\sqrt{N}}\right) \quad .$$

Distribution of $\blacklozenge_{\blacklozenge,T}(U_T)$

- Wind speed standard deviations identically Gaussian distributed
- Thus:

$$\sigma_{\sigma,T} \in \frac{\sigma_\sigma}{\sqrt{N-1}} L1(N-1) \quad ,$$

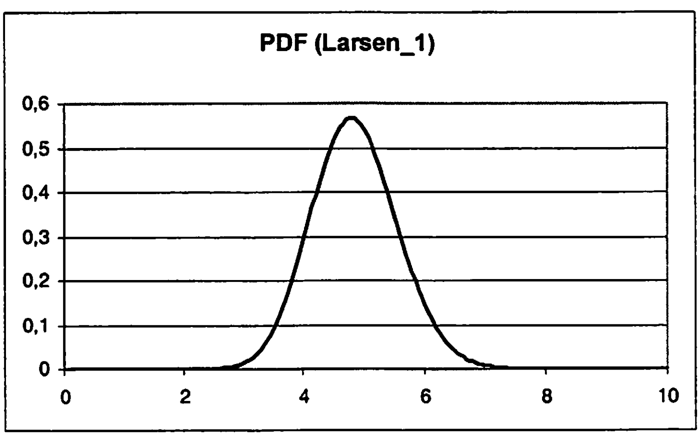
$$F(y) = \frac{1}{\Gamma\left(\frac{N-1}{2}\right)} \int_0^{\frac{y^2}{2}} z^{\frac{N-1}{2}-1} e^{-z} dz = \frac{1}{\Gamma\left(\frac{N-1}{2}\right)} \gamma\left(\frac{N-1}{2}, \frac{y^2}{2}\right) \quad ,$$

Distribution of DTI

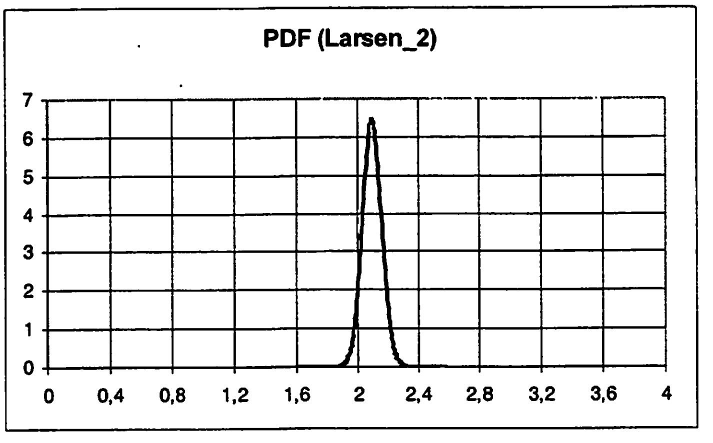
- CDF obtained from a convolution of
  - PDF of the standard deviation of the wind speed standard deviation
  - CDF of the sample mean of the wind speed standard deviations

$$D(\sigma_{d,T};N,C,\mu_\sigma,\sigma_\sigma)=\int_{\sigma_{\sigma,T}=0}^{C\sigma_{d,T}} \frac{\sigma_\sigma}{\sqrt{N-1}} f\left(\frac{\sigma_{\sigma,T}}{C}\right) \frac{\Phi\left(\sigma_{d,T}-\sigma_{\sigma,T};\mu_\sigma,\frac{\sigma_\sigma}{\sqrt{N}}\right)}{\left(1-\Phi\left(0;\mu_\sigma,\frac{\sigma_\sigma}{\sqrt{N}}\right)\right)} d\sigma_{\sigma,T}\ .$$

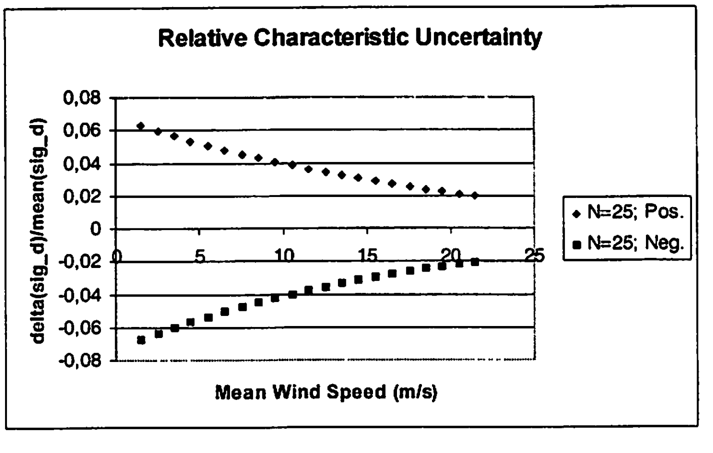
Results (N=25)



Results (Gedser 21.5m/s; N=25)



Application



Conclusion

- An approximate analytical model, describing the distribution of the design standard deviation, has been established
- Subsequently, the model has been used to quantify the relative characteristic uncertainty of the design standard deviations
- The estimated relative characteristic uncertainties are seen to decrease with increasing mean wind speeds, and decrease with increasing sample size

Calibration of Partial Safety Factors and Eurocodes

John Dalsgaard Sørensen
Aalborg University, Aalborg, Denmark

- Calibration of partial safety factors
- Eurocodes
- Wind actions in Eurocodes

Code Format - Denmark

Design load effect:

$$S_d = S(\gamma_G G_c\,,\ \gamma_Q Q_c\,,\ \psi_2 Q_{c2}\,,\ldots,\ \psi_n Q_{cn})$$

Permanent action:

γ_G	partial safety factor
G_c	characteristic value (50 % quantile)

Variable actions:

γ_Q	partial safety factor and
Q_c	characteristic value (98 % quantile)
ψ	load combination factor

Design values for strength parameters:

$$m_d = \eta \frac{m_c}{\gamma_m}$$

m_c characteristic strength (5 % quantile)

η conversion factor

$\gamma_m = \gamma_0 \gamma_1 \gamma_2 \gamma_3 \gamma_4 \gamma_5$ partial safety factor

γ_0 consequences of failure – safety class
(low: 0.9 ; normal: 1.0 ; high: 1.1)

γ_1 type of failure
(ductile with reserve: 0.9 ; without reserve: 1.0 ; brittle: 1.1)

γ_2 unfavorable differences from characteristic value of material parameter

γ_3 uncertainty in the computational model
(good: 0.95 ; normal: 1.0 ; bad: 1.1)

γ_4 uncertainty with determination of material parameter
(large: 0.95 ; average: 1.0 ; small: 1.1)

γ_5 control
(extended: 0.95 ; normal: 1.0 ; reduced: 1.1)

Load combinations (LC)

Serviceability

LC 1: serviceability

Ultimate limit states

LC 2.1: variable action dominating and unfavorable permanent action

LC 2.3: permanent action dominating and unfavorable permanent action

LC 2.2: favorable permanent action (lift and tilting / static equilibrium)

LC 2.4: fatigue

Accidental

LC 3.1 Collision, explosion,...

LC 3.2 Removal of structural members

LC 3.3 Fire

Reliability-based Calibration of Partial Safety Factors

1. Selection of typical example structures
2. Identification of failure modes
3. Code format
4. Stochastic model
5. Reliability level in 1982 code
6. Calibration of new partial safety factors such that average reliability level is unchanged - LC 2.1 and 2.3
7. Verification

Example structures

- simply supported beams of reinforced concrete
- simply supported beams of steel
- simply supported beams of glued laminated timber
- short columns of concrete
- short columns of steel
- short columns of glued laminated timber
- central loaded footing (foundation) on sand and clay
- concrete gravity wall

Six different load cases with different ratios between permanent and variable actions

Variable actions: divided in imposed and environmental actions

Stochastic model

Variable	COV	Distribution
Permanent loads:		
Permanent action	10 %	N
self-weight: concrete	6 %	N
self-weight: steel	4 %	N
self-weight: timber	6 %	N
Variable loads:		
Imposed load	20 %	G
Environmental load	40 %	G
Strengths:		
Concrete comp. strength	15 %	LN
Reinforcement	5 %	LN
Steel	5 %	LN
Glued laminated timber	15 %	LN
Eff. friction angle	3.3 %	LN
Undrained shear strength – clay	16 %	LN
Model unc. concrete	5 %	LN
Model unc. steel	3 %	LN
Model unc. timber	5 %	LN
Model unc. foundation	15 %	LN

N: normal, LN: lognormal, G: Gumbel

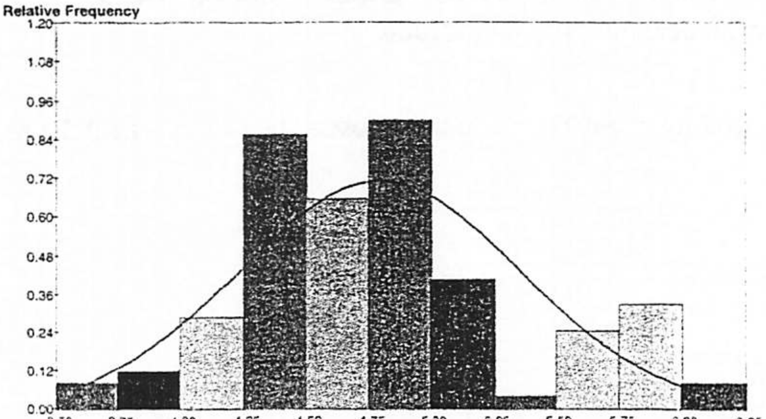
Wind actions: $Q = PX$

P wind pressure
(Gumbel distributed with COV=0.25)

X model uncertainty (form factors etc.)
(Gumbel distributed with COV=0.22)

Reliability indices for example structures using 1982 codes:

	Average value	Standard deviation
Beam – concrete	5.39	0.62
Beam – steel	5.06	0.64
Beam – timber	4.58	0.27
Column – concrete	4.64	0.26
Column – steel	5.10	0.66
Column – timber	4.58	0.27
Foundation on sand	4.61	0.45
Foundation on clay	4.37	0.76
Gravity wall	4.89	
Total	4.79	0.56

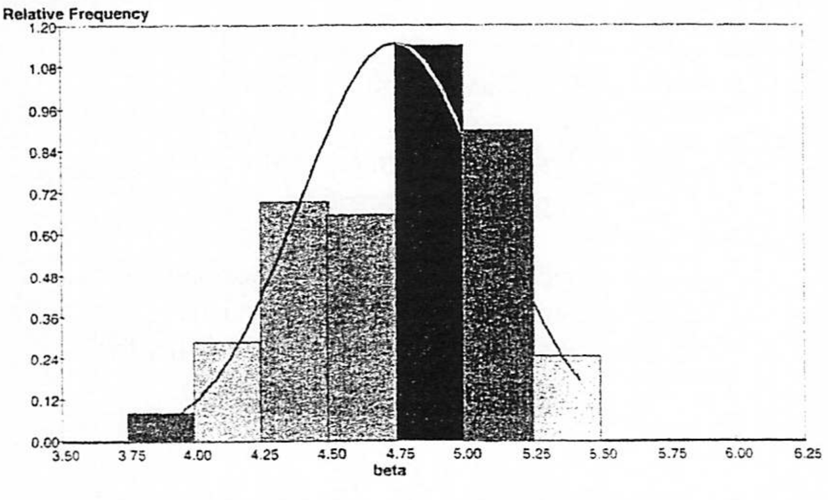


Calibration of new partial safety factors for LC 2.1 / 2.3

		1982 code γ_f / γ_2	Final γ_f / γ_2
γ_{G1}	Permanent action (LC 2.1)	1.0	1.0
γ_{Q1I}	Imposed action (LC 2.1)	1.3	1.3
γ_{Q1E}	Environmental action (LC 2.1)	1.3	1.5
γ_{G3}	Permanent action (LC 2.3)	1.15	1.15
γ_{Q3I}	Imposed action (LC 2.3)	-	1.0
γ_{Q3E}	Environmental action (LC 2.3)	-	1.0
γ_R	Reinforcement	1.32	1.3
γ_C	Concrete	1.58	1.5
γ_S	Steel	1.42	1.3
γ_T	Glued laminated timber	1.35	1.5
γ_φ	Friction angle	1.2	1.2
γ_{C_u}	Undrained shear strength	1.8	1.8

Reliability indices – new code:

	Average value	Standard deviation
Beam – concrete	4.69	0.34
Beam – steel	4.64	0.39
Beam – timber	4.81	0.22
Column – concrete	4.81	0.20
Column – steel	4.67	0.41
Column – timber	4.81	0.22
Foundation on sand	4.81	0.48
Foundation on clay	4.68	0.50
Gravity wall	5.10	
Total	4.79	0.35



Discussion of Reliability Level

Eurocode EN(V) 1990: Basis of Structural Design:

- average reliability index: 5.0
- reliability level in Eurocodes (Eq. 6.10a and 6.10b) is quite non-uniform:
  - high reliability level for structures with dominating permanent load (γ_G=1.35)
  - smaller reliability level for structures with dominating variable load (γ_Q=1.5)

EUROCODES

EN 1990	**Eurocode 0: Basis of Structural Design**
EN 1991	**Eurocode 1: Actions on structures**
EN 1992	Eurocode 2: Design of concrete structures
EN 1993	Eurocode 3: Design of steel structures
EN 1994	Eurocode 4: Design of composite steel and concrete structures
EN 1995	Eurocode 5: Design of timber structures
EN 1996	Eurocode 6: Design of masonry structures
EN 1997	Eurocode 7: Geotechnical design
EN 1998	Eurocode 8: Design of structures for earthquake Resistance
EN 1999	Eurocode 9: Design of aluminum structures

EN 1990 Eurocode 0: Basis of Structural Design

1. General
2. Requirements
3. Principles of limit state design
4. Basic variables
5. Structural analysis and design assisted by testing
6. Verification by partial factor method

Annex A1	Application for buildings (normative)
Annex A2	Application for bridges (normative)
Annex B	Management of structural reliability for construction works (informative)
Annex C	Basic for partial factor design and reliability analysis (informative)
Annex D	Design assisted by testing (informative)

Ultimate limit states

Combination of actions:

$$\gamma_G G_c + \gamma_{Q_1} Q_{c,1} + \gamma_{Q_2}\psi_{0,2}Q_{c,2} + \gamma_{Q_3}\psi_{0,3}Q_{c,3} + \ldots \qquad (6.10)$$

or

$$\gamma_G G_c + \gamma_{Q_1}\psi_{0,1}Q_{c,1} + \gamma_{Q_2}\psi_{0,2}Q_{c,2} + \gamma_{Q_3}\psi_{0,3}Q_{c,3} + \ldots \qquad (6.10a)$$

$$\xi\gamma_G G_c + \gamma_{Q_1} Q_{c,1} + \gamma_{Q_2}\psi_{0,2}Q_{c,2} + \gamma_{Q_3}\psi_{0,3}Q_{c,3} + \ldots \qquad (6.10b)$$

Combinations to be verified:
A: EQU: Static equilibrium
B: STR/GEO: Structural members
C: GEO: Resistance of ground

The γ and ξ values may be set by the National annex.

The following values for γ and ξ are recommended when using expressions 6.10, or 6.10a and 6.10b in EQU and STR/GEO

$\gamma_{Gj,sup} = 1{,}35$
$\gamma_{Gj,inf} = 1{,}00$
$\gamma_{Q,1} = 1{,}50$ where unfavourable (0 where favourable)
$\gamma_{Q,i} = 1{,}50$ where unfavourable (0 where favourable)

$\xi = 0{,}85$ (so that $\xi\gamma_{Gj,sup} = 0{,}85 \times 1{,}35 \cong 1{,}15$).

EN 1991 Eurocode 1: Actions on Structures

EN 1991-1-1 Densities, self-weight, imposed loads for buildings
EN 1991-1-2 Actions on structures exposed to fire
EN 1991-1-3 Snow loads
EN 1991-1-4 Wind actions
EN 1991-1-5 Thermal actions
EN 1991-1-6 Actions during execution
EN 1991-1-7 Accidental actions from impact and explosion

EN 1991-2 Traffic loads on bridges
EN 1991-3 Actions induced by cranes and machinery
EN 1991-4 Actions in silos and tanks

EN 1991-1-4 Wind actions

1. General
2. Design situations
3. Modelling of wind action
4. Wind velocity and velocity pressure
5. Wind actions
6. Structural factor
7. Pressure and force coefficients
8. Wind actions on bridges

Annex A	Terrain effects
Annex B	Detailed procedure for structural factor B.1 General B.2 Procedure 1 B.3 Procedure 2
Annex C	Vortex shedding and aeroelastic instabilities
Annex D	Wind actions on bridges
Annex E	Dynamic characteristics of structures

Basic wind velocity

$$v_b = c_{dir} c_{års} v_{b,0}$$

$v_{b,0}$ fundamental value of basic wind velocity (24-27 m/s)
c_{dir} directional factor
$c_{års}$ season factor

Basic velocity pressure q_b

$$q_b = \tfrac{1}{2} \rho v_b^2 = c_{dir}^2 c_{års}^2 q_{b,0}$$

ρ air density = 1,25 kg/m³
$q_{b,0}$ fundamental value of basic wind pressure, $q_{b,0} = \tfrac{1}{2} \rho v_{b,0}^2$

Mean wind variation with height

$$v_m(z) = c_r(z) c_t(z) v_b$$

$c_r(z)$ roughness factor
$c_t(z)$ orography factor

10 minutes mean wind velocity pressure

$$q_m(z) = c_r^2(z) c_t^2(z) q_b$$

Roughness factor

$$c_r(z) = k_t \ln(z / z_0)$$

$k_t = 0.19\left(\dfrac{z_0}{z_{0,II}}\right)$ terrain factor; $z_{0,II} = 0.05$ m

z_0 roughness length

Wind turbulence

Statistical standard deviation of turbulence

$$\sigma_v = k_t v_b$$

Turbulence intensity

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_t}{c_0(z)} \frac{1}{\ln(z / z_0)}$$

Wind distribution over frequencies

Spectral density function:

$$R_v(z,n) = \frac{nS_v(z,n)}{\sigma_v^2} = \frac{6{,}8 f_L(z,n)}{(1+10{,}2 f_L(z,n))^{5/3}}$$

Dimensionless frequency:

$$f_L(z,n) = \frac{nL(z)}{v_m(z)}$$

n frequency in Hz

Length scale of turbulence:

$$L(z) = L_t\left(\frac{z}{z_t}\right)^{0{,}3}$$

z_t=10 m reference height
L_t=100 m reference length scale

Peak velocity pressure

$$q_p(z) = (1+2k_p I_v(z))q_m(z)$$

k_p peak-factor=3,5

Wind forces

$$F_w = q_p c_s c_d c_f A_{ref}$$

Structural factor (quasi-static response):

$$c_s c_d = \frac{1+2k_p I_v(z_{ref})\sqrt{B^2}}{1+2k_p I_v(z_{ref})}$$

k_p peak-factor = 3,5
I_v turbulence intensity
B^2 background factor, taking into account lack of full correlation of pressure on the surface of the structure. Conservatively: B^2=1

For rectangular areas:

$$B^2 = \frac{1}{1+\frac{3}{2}\sqrt{\left(\frac{b}{L(z_{ref})}\right)^2+\left(\frac{h}{L(z_{ref})}\right)^2+\left(\frac{b}{L(z_{ref})}\frac{h}{L(z_{ref})}\right)^2}}$$

Dynamic response – Structural factor

$$c_s c_d = \frac{1 + k_p 2 I_v(z_{ref})\sqrt{B^2 + R^2}}{1 + 7 I_v(z_{ref})}$$

k_p peak-factor

I_v intensity of turbulence

z_{ref} reference height

B^2 background factor, taking into account the quasistatic response

R^2 resonance factor, taking into account turbulence in resonance with the structure

$$R^2 = \frac{\pi^2}{2(\delta_s + \delta_a)} R_v(z_{ref}, n_1) K_s(n_1)$$

δ_s structural damping (logarithmic decrement)

δ_a aerodynamic damping (logarithmic decrement)

R_v spectral density function of wind turbulence

K_s size reduction function

Size reduction function

Normalized co-spectrum

$$K(y_1, y_2, z_1, z_2, n) = \exp\left(\frac{-n\sqrt{c_y^2 (y_1 + y_2)^2 + c_z^2 (z_1 + z_2)^2}}{\tfrac{1}{2}\left(v_m(z_1) + v_m(z_2)\right)} \right)$$

Size reduction factor

$$K_s(n) = \frac{\int_0^h \int_0^b \int_0^h \int_0^b g(y_1, z_1) g(y_2, z_2) K(y_1, z_1, y_2, z_2, n) dy_1 dz_1 dy_2 dz_2}{\int_0^h \int_0^b \int_0^h \int_0^b g(y_1, z_1) g(y_2, z_2) dy_1 dz_1 dy_2 dz_2}$$

$$\cong \frac{1}{1 + \sqrt{(G_y \phi_y)^2 + (G_z \phi_z)^2 + \left(\frac{2}{\pi} G_y \phi_y G_z \phi_z\right)^2}}$$

where

$\phi_y = c_y b n / v_m(z_{ref})$ $\phi_z = c_z h n / v_m(z_{ref})$ $c_y = c_z = 10$

mode shape	uniform	linear	parabolic	sinusoidal
$g_\alpha(\alpha)$	1	α	α^2	$\sin(\alpha)$
G	½	3/8	5/18	$4/\pi^2$
K	1	3/2	5/3	$4/\pi$

$g_z(z) = v_m(z) c(z) \zeta_z(z)$ $g_y(y) = v_m(y) c(y) \zeta_y(y)$

$c(z)$ $c(y)$ shape functions

$\zeta_z(z)$ $\zeta_y(y)$ mode shapes in z- and y-direction

Knut Ronold

DNV

DNV – probabilistic analysis of wind turbines

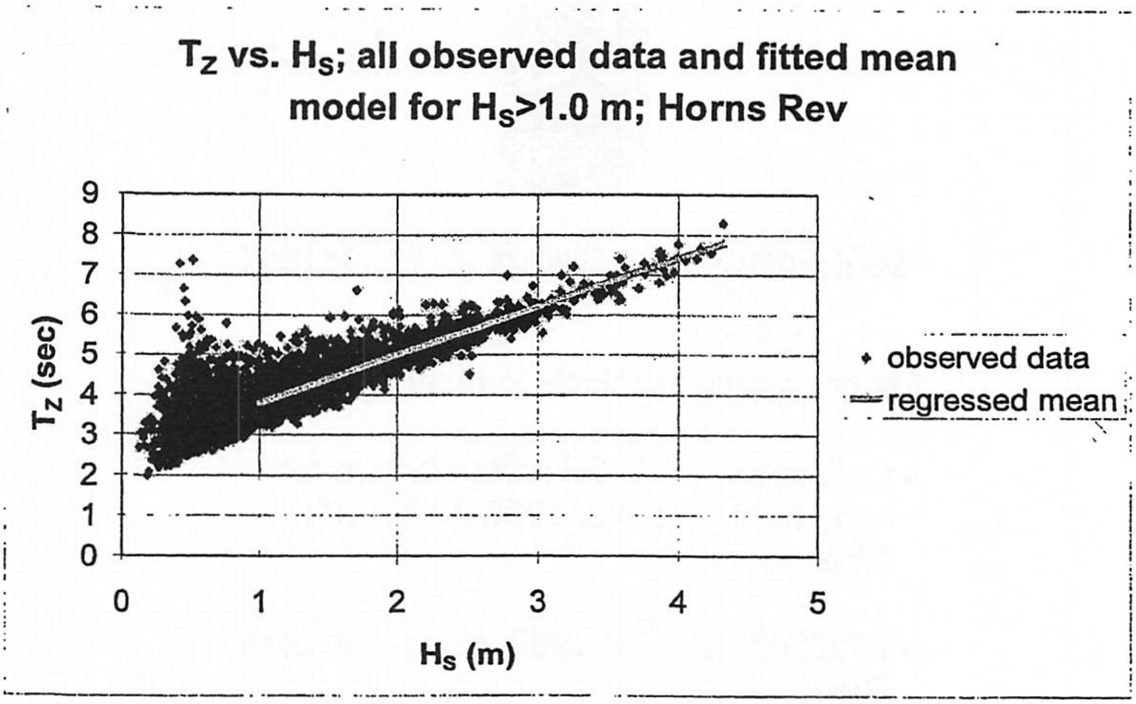
Major activities/projects in recent years

- Calibration of partial safety factors for wind turbine rotors, 1997-2000, with Risø
- PRODETO, 1996-1998, subcontractor to Risø
- Design basis for offshore wind turbines, 1999-2000, cooperation with SEAS, Risø etc.
  - joint probability distributions of wave and wind climate variables
  - application to foundation stability in cyclic loading

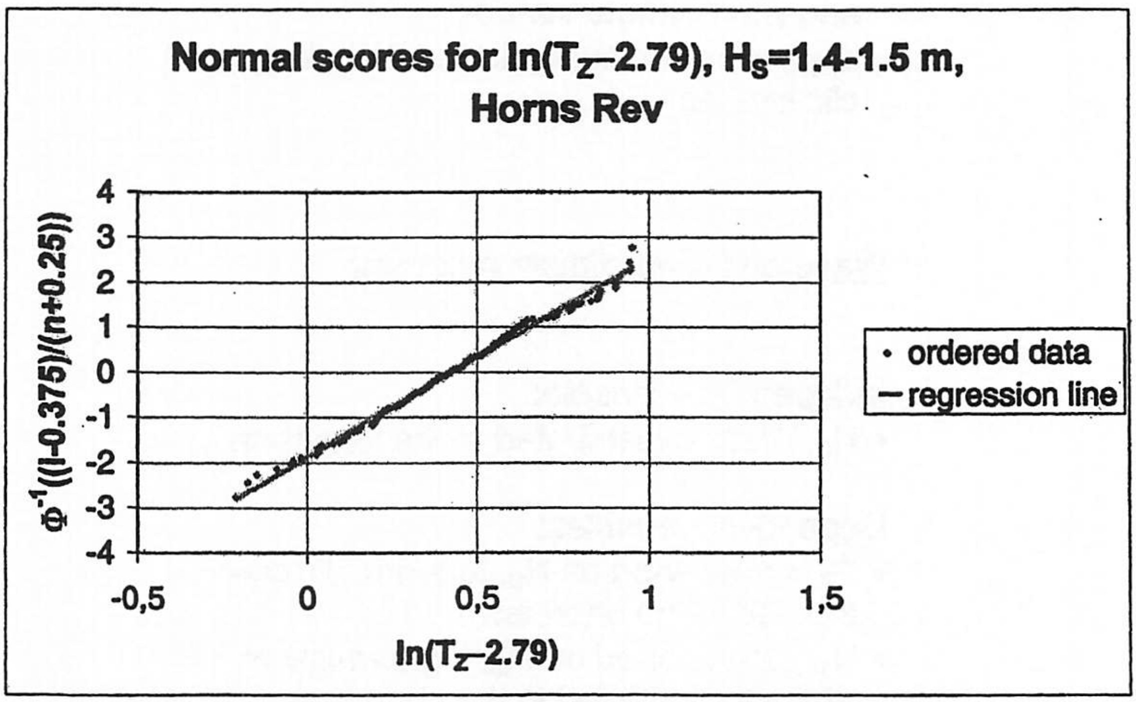
Wave and wind climate modelling

Independent variable:
- H_S, Weibull distributed in the long term

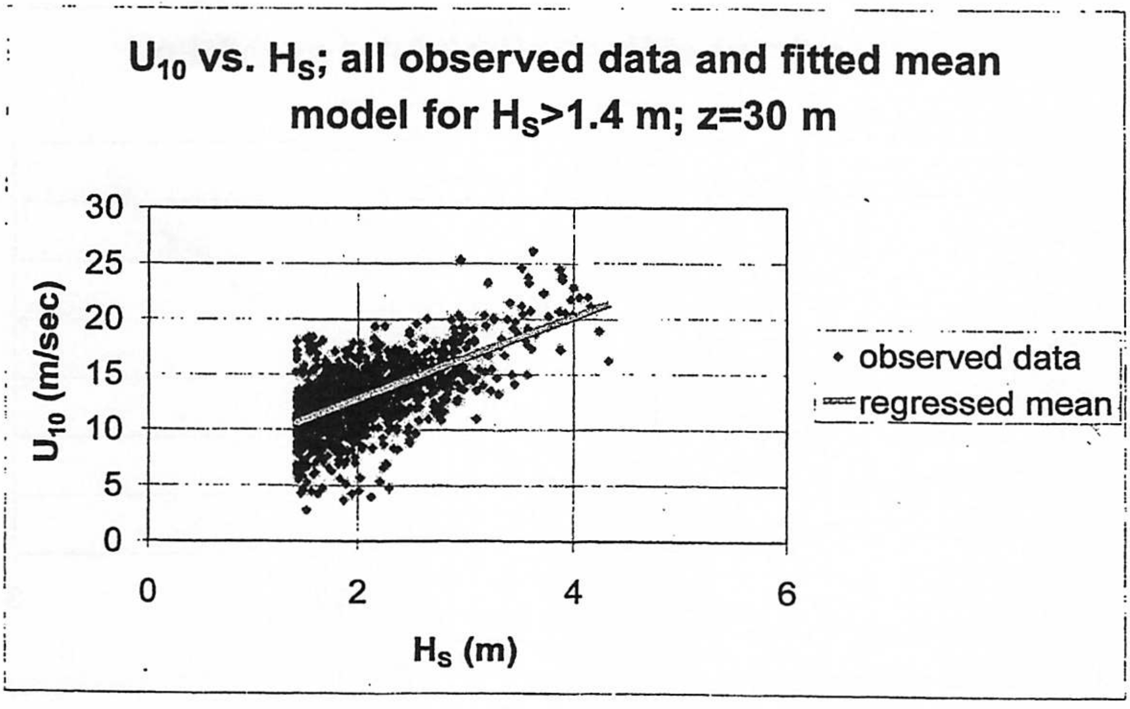
Dependent variables:
- T_Z, conditioned on H_S, lognormally distributed in the short term
- U_{10}, conditioned on H_S, lognormally or Weibull distributed in the short term (U_{10} as independent variable is Weibull distributed in the long term)
- σ_U, conditioned on U_{10}, lognormally or Frechet distributed in the short term

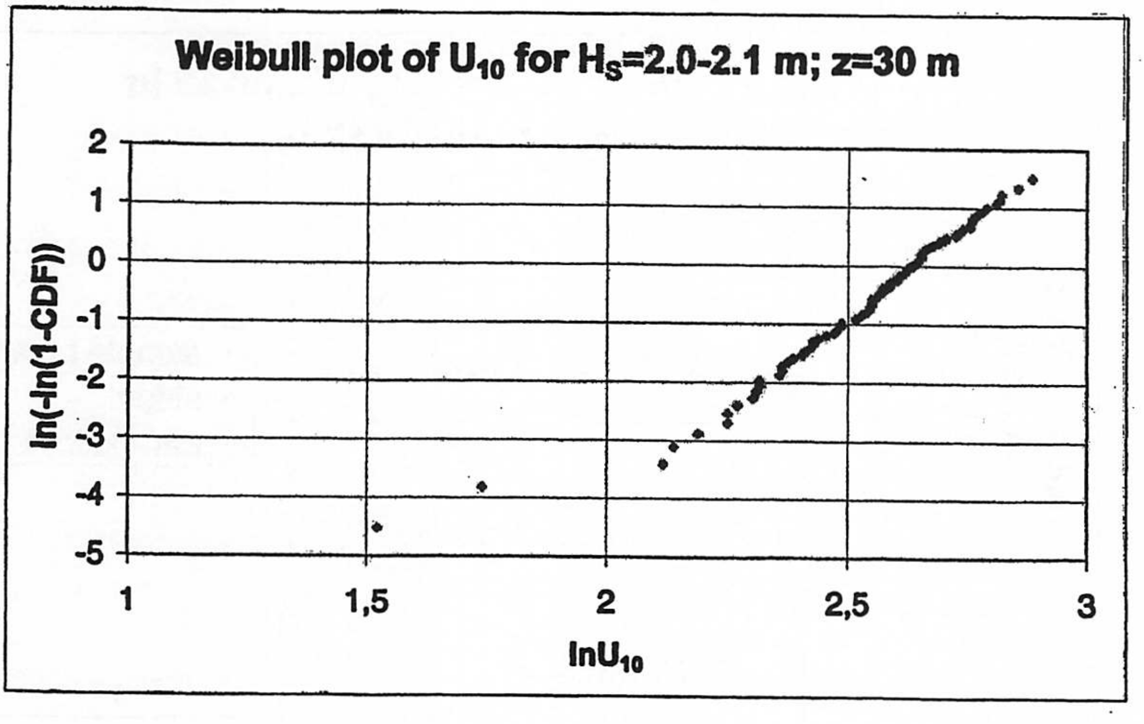


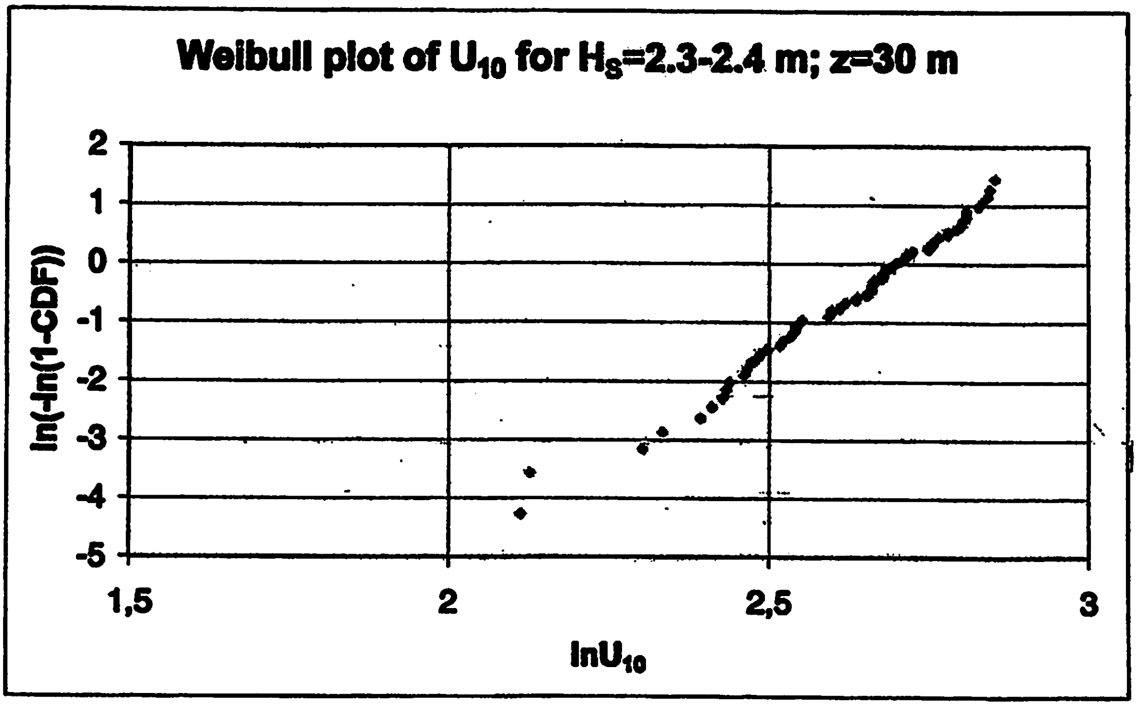
T_Z vs. H_S; all observed data and fitted mean model for H_S>1.0 m; Horns Rev
T_Z (sec)
H_S (m)
observed data
regressed mean
0
1
2
3
4
5
6
7
8
9
0
1
2
3
4
5

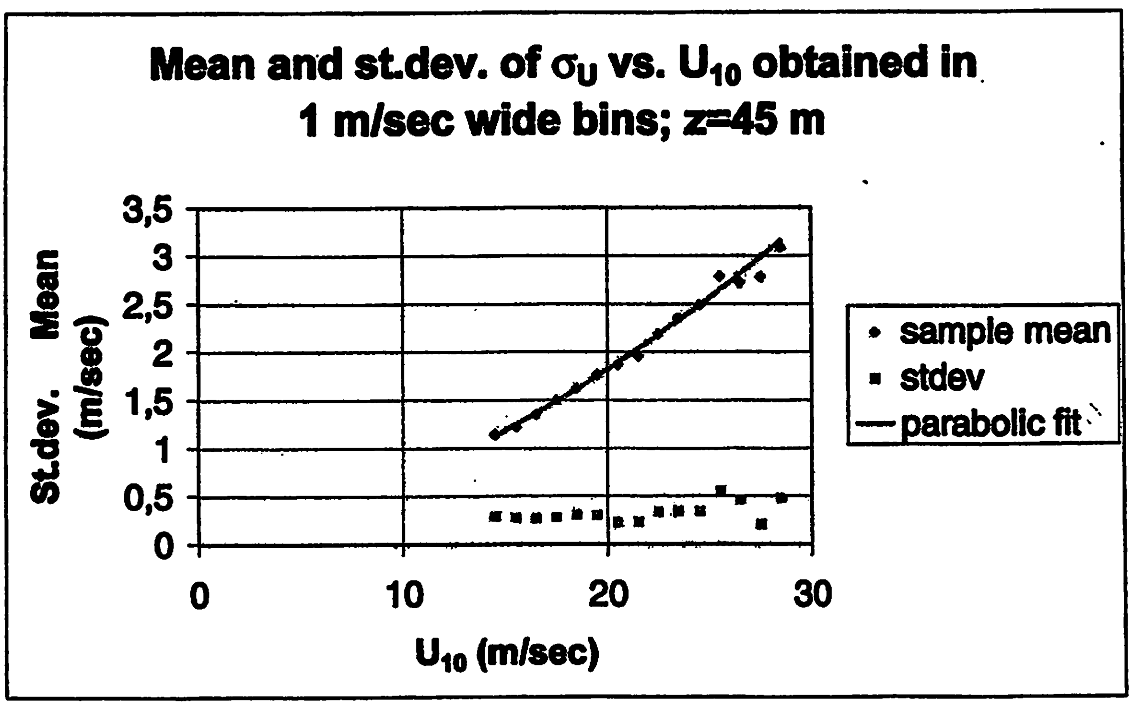


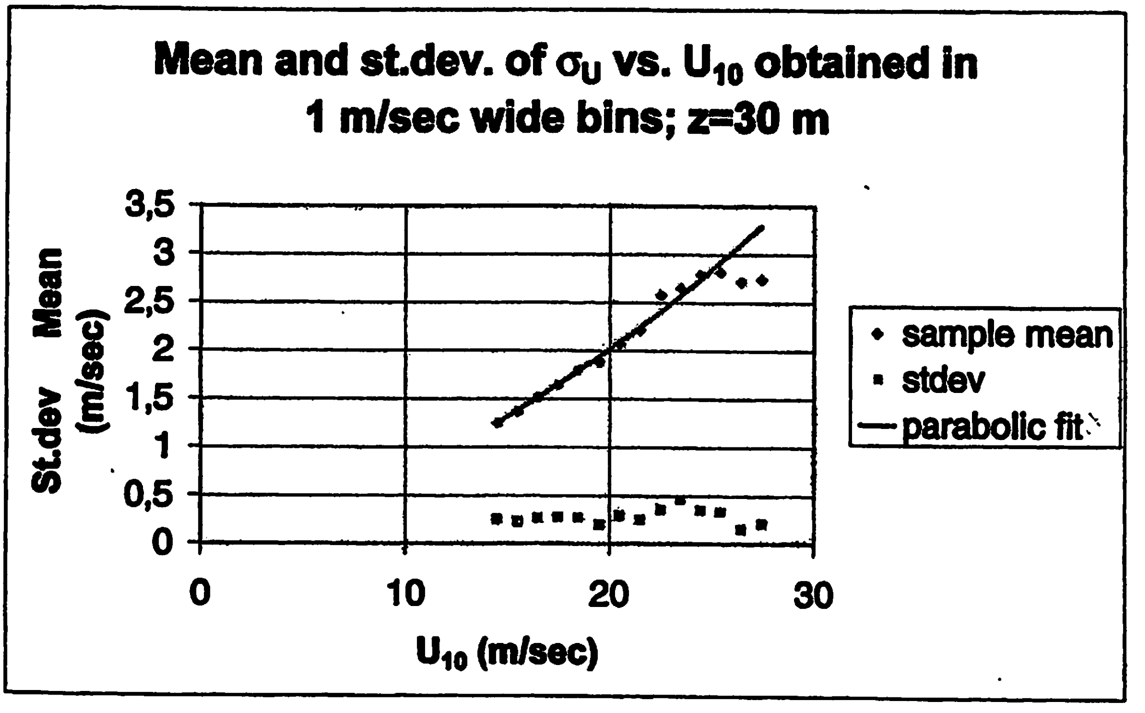
Normal scores for ln(T_Z–2.79), H_S=1.4-1.5 m, Horns Rev
$\Phi^{-1}((I-0.375)/(n+0.25))$
ln(T_Z–2.79)
ordered data
regression line
4
3
2
1
0
-1
-2
-3
-4
-0,5
0
0,5
1
1,5

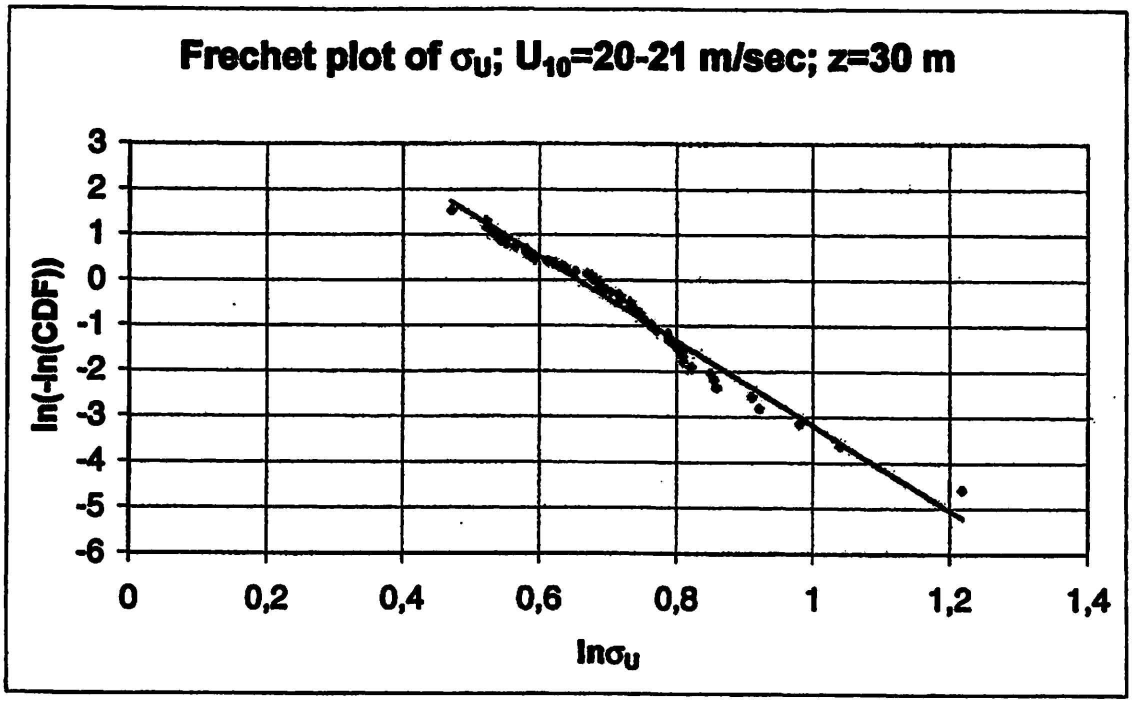

U10 vs. HS; all observed data and fitted mean model for HS>1.4 m; z=30 m
U10 (m/sec)
HS (m)
observed data
regressed mean
0
5
10
15
20
25
30
0
2
4
6


Weibull plot of U10 for HS=2.0-2.1 m; z=30 m
ln(-ln(1-CDF))
lnU10
2
1
0
-1
-2
-3
-4
-5
1
1,5
2
2,5
3


Weibull plot of U_{10} for H_S=2.3-2.4 m; z=30 m
2
1
0
-1
-2
-3
-4
-5
ln(-ln(1-CDF))
1,5
2
2,5
3
lnU_{10}


Mean and st.dev. of σ_U vs. U_{10} obtained in 1 m/sec wide bins; z=45 m
3,5
3
2,5
2
1,5
1
0,5
0
St.dev. Mean (m/sec)
0
10
20
30
U_{10} (m/sec)
sample mean
stdev
parabolic fit


Mean and st.dev. of σ_U vs. U_{10} obtained in 1 m/sec wide bins; z=30 m
St.dev Mean (m/sec)
3,5
3
2,5
2
1,5
1
0,5
0
0
10
20
30
U_{10} (m/sec)
sample mean
stdev
parabolic fit


Frechet plot of σ_U; U_{10}=20-21 m/sec; z=30 m
ln(-ln(CDF))
3
2
1
0
-1
-2
-3
-4
-5
-6
0
0,2
0,4
0,6
0,8
1
1,2
1,4
$\ln\sigma_U$

References:

Knut O. Ronold, Jakob Wedel-Heinan, Carl J. Christensen
Reliability-based fatigue design of wind-turbine rotor blades
Engineering Structures 21 (199) 1101-1114

Knut O. Ronold, Gunner C. Larsen
Reliability-based design of wind-turbine rotor blades against failure in ultimate loading
Engineering Structures 22 (2000) 565-574

Knut O. Ronlold, Carl J. Christensen
Optimization of a design code for wind-turbine rotor blades in fatigue
Engineering Structures (2001) 993-1004

Bayesian Analysis Applied to Statistical Uncertainties of the Extreme Responses Distribution of an Offshore Wind Turbine

P.W. Cheng
Section Wind Energy TU Delft Netherlands

Abstract

The statistical uncertainties concerning the extreme response distribution is considered here. The extreme responses are the flap moment at the blade root and the overturning moment of the support structure of an offshore wind turbine situated in the North sea. The statistical uncertainties treated here are the uncertainties concerning the choice of distribution and uncertainties concerning the distribution parameters. The uncertainties are treated with Bayesian analysis. The inclusion of the uncertainties has only marginal effect for the long-term estimates of extreme responses when non informative priors for the distribution parameters are used. The inclusion of uncertainties may have larger effect for real measurement data.

1 Statistical Uncertainties

The estimate of extreme response beyond the data length is ridden of uncertainties. There many type of uncertainties present in the whole process of response estimation. In this context we only consider the statistical uncertainties that arise in fitting of the parametric models, such uncertainties of the distribution, parameters of the distributions. We try to incorporate the influence of the uncertainties using Bayesian analysis.

1.1 Bayesian analysis of the uncertainties

The result of the simulation has to be subject to statistical analysis. The uncertainties that are associated with the statistical analysis, are: the choice of the distribution type and the parameters of the distribution. The choice of the distribution in most cases can not be determined unambiguously, thus a subjective choice has to be made. The uncertainties concerning the parameters of the distribution can be considered using the Bayesian analysis. The core of the Bayesian analysis is the Bayes theorem[6]

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{1}$$

where $P(A|B)$ denotes the conditional probability of A given B. The subjectivity of the Bayesian analysis lies in the term $P(A)$ which represents the prior probability distribution of the parameters. The $P(A|B)$ is the so called posterior distribution. The choice of the prior distribution is rather arbitrary. It is usually based on a subjective judgement about the character of the distribution (by experience etc.). Therefore, a Bayesian analysis is not a sound procedure in the eyes of mathematical statistician because of this subjective element. However, in an engineering approach where the decision making process can not always be made based on an objective judgement, the Bayesian analysis is widely accepted.

As an example of the Bayesian analysis, we consider the extreme flap moment of the blade fitted to a Weibull distribution The Bayesian theorem can be written as

$$f''(\boldsymbol{\theta}) = C \cdot P(data|\boldsymbol{\theta}) \cdot f'(\boldsymbol{\theta}) \tag{2}$$

f'' is the posterior and f' is the prior distribution of the Weibull distribution parameters. $\boldsymbol{\theta}$ represents the vector of the distribution parameters and C is a normalisation factor to be determined. $P(data|\boldsymbol{\theta})$ is the so called data likelihood function as defined in Equation 3

$$X_{mle} = \max\left\{\prod f(Y_i|\mathbf{X})\right\} \tag{3}$$

,where $\prod f(Y_i|\mathbf{X})$ is the so called data likelihood function.In this case we obtain a three dimensional probability density function of the distribution parameters and the hyper-volume of the functions is normalised by the constant C to unity.

The spreading in the uncertainties of the distribution parameters can be taken into account through the total probability theorem,

$$F(X) = \iiint F(X|\boldsymbol{\theta}) f''(\boldsymbol{\theta}) \mathrm{d}\boldsymbol{\theta} \tag{4}$$

$F(X|\boldsymbol{\theta})$ is ,in this case. the conditional distribution of the peak flap moment given a set of distribution parameters.

With the same manner that the uncertainties of the parameters are dealt with, it can be applied to the uncertainties in the distribution type.

Instead of the continuous density distribution of the parameters we have a prior set of weighting factors for different types of distributions.

$$f''(\mathbf{F}_i) = C \cdot P(data|\mathbf{F}_i) \cdot f'(\mathbf{F}_i) \tag{5}$$

$\mathbf{F}_i$ represents the different distribution type taken into consideration. Using Equation 5 the posterior weighting factors for the different distributions functions are obtained. The posterior weighting factors are taken in to account analoguely as described in the Equation 4 where the summation sign replaces the integration sign.

$$F(x) = \sum_i F(X|\mathbf{F}_i) f''(\mathbf{F}_i) \tag{6}$$

Notice that the Equation 4 takes into account all the possible variation of the distribution parameters while the Equation 6 can only take a finite number of distribution function into account. This implies also that the end result depends strongly on the selection of distribution function. Thus, once should make visualisations of the sample data in form of P-P or Q-Q plots to determine if the distribution functions chosen are appropriate.

1.2 Uncertainties in the choice of distribution

The choice of distribution model is surrounded by subjective decisions. However, there are different diagnostics to distinguish those valid ones from those 'less valid' ones, but even these diagnostics can not be always free of subjective elements. Before we proceed to choose the distribution function we can have some description of the data first. Such descriptor can be the mean, median, variance, skewness etc. This give us a general picture of the data. For the sake of example we use a data set consisting of 50 maxima taken from 50 simulation of 10 minutes. The maxima are the extreme flap moment at the blade root. The different statistical descriptors are shown in Table 1.

From table one we can see that the data has a small coefficient of variation and it is positively skewed . The kurtosis is less than 3 (Normal distribution), which may indicate a less fat tail than the Gaussian distribution. We first fit it to 4 different functions, the Normal distribution, the Gumbel distribution, the Frechét distribution and the Weibull distribution. The distribution are fitted with the least square criterion. We also fitted the data to the Generalised Extreme Value (GEV) distribution [5], however, the fit yields a reverse Weibull distribution and this distribution is associated with a right end point. Considering that we will extrapolate the response distribution to a much longer period, this would be a serious limitation. For this reason we do not consider the GEV fit here.

The test for the goodness of fit [2]is carried for all the four distributions using the χ^2 test. For the present sample size of 50 data point we choose a bin size such that is about $\sigma/3$,where σ is the sample standard deviation. With a significance level of 95%, the null hypothesis can not be rejected for all the 4 distributions. However, as mentioned before the bin size is critical for the χ^2 test. In case we choose a larger bin size the test result can lead to the rejection of the null hypothesis. There is also recommendations about choosing the bin size such that at least 5 samples will fall into a bin or about collapsing the bins if the number of samples in the bin is too small. However, one should be careful with such manipulation.

We also carried out a distribution free test, the Kolmogorov-Smirnov (KS) test. This test is recommended if the sample size is small. It measure the absolute deviation of the fitted distribution from the sample distribution. According to the KS test the null hypothesis can not be rejected. Another class of test is the quadratic test. One of the quadratic tests is the Anderson-Darling test, it measure the deviation of the cumulative probability from the uniform distribution, giving a higher weight to the value in the tail region. If the detection of deviation in the tail region is important, the Anderson-Darling test is recommended.

Figure 1 shows the sample distribution function with different fits. The Gumbel fit and the Frechét fit is almost identical, because the shape factor for the Frechét distribution is in the order of 10^8 and the Frechét distribution converges to Gumbel distribution if shape factor $\alpha \to \infty$.

It can be seen that the Gumbel has the heaviest tail followed by Weibull and Normal distribution. Since a visual inspection can not offer much help to choose a suitable distribution we analyse the statistical descriptors of the distributions. The mean and standard deviation of the Normal distribution is identical to the samples mean and standard deviation. The rest can be calculated from the distribution functions. Table 1 shows the first four descriptors of the distribution functions

From the Table 1 it can be seen that the mean and standard deviation are good approximated by the distribution functions. The difference lies in the skewness and the kurtosis. The sample suggest a slight positive skewness and the a kurtosis that is below of the Normal distribution. The Gumbel has a heavier tail which is independent of the scale and location parameter, thus it can be expected that it will yield also the highest estimate. Weibull is a more appropriate choice, which can models the skewed samples without producing a much heavier tail because of the extra flexibility of the shape parameter. The Normal distribution

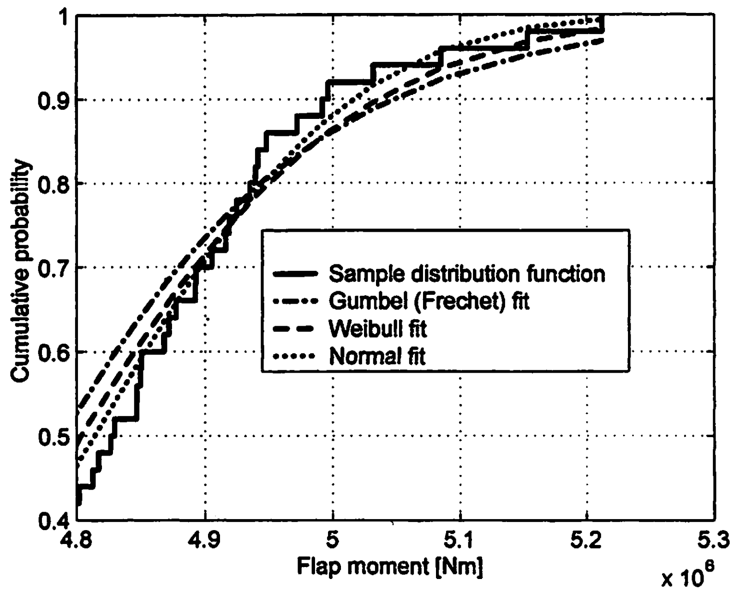


Figure 1: Sample data fit to different distribution functions

Table 1: statistical descriptors of the sample data and distribution functions

	Sample	Weibull	Gumbel	Normal
mean	$4.81{\cdot}10^6 Nm$	$4.82{\cdot}10^6 Nm$	$4.81{\cdot}10^6 Nm$	$4.81{\cdot}10^6 Nm$
standard deviation	$0.15{\cdot}10^6 Nm$	$0.15{\cdot}10^6 Nm$	$0.17{\cdot}10^6 Nm$	$0.15{\cdot}10^6 Nm$
skewness	0.22	0.69	1.13	0
kurtosis	2.58	3.2	5.4	3

is also acceptable considering the light tail of the sample. If there is any indication that the distribution is heavier than Normal distribution, then Weibull distribution is a better choice.

1.2.1 Bayesian Analysis of the distribution choice

Using the procedure described in the previous section one can take into account the uncertainty of the distribution choice in a semi-empirical way. Again we have chosen the 3 distributions that have been tested before, and the sample data are the extreme flap moment taken from 50 simulations with a mean wind speed of 15 m/s.

Table 2 shows the 99 percentiles of the distributions of the maximum flap moment for different distribution functions. It also shows the posterior probabilities of the distribution functions in percentage of

Table 2: participation factors and fractile values of the distribution functions in a Bayesian analysis

Distribution	participation	99%	100 year
Gumbel	14%	$5.36 \cdot 10^6 Nm$	$6.13 \cdot 10^6 Nm$
Normal	0.8%	$5.18 \cdot 10^6 Nm$	$5.43 \cdot 10^6 Nm$
Weibull	84%	$5.25 \cdot 10^6 Nm$	$5.62 \cdot 10^6 Nm$
Bayes		$5.26 \cdot 10^6 Nm$	$5.69 \cdot 10^6 Nm$

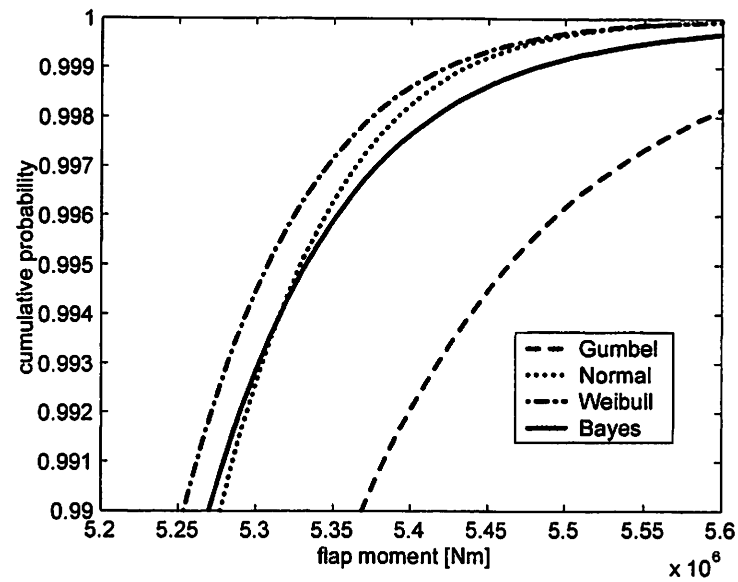


Figure 2: Cumulative probability of the extreme flap moment with different distribution models, the mean wind speed is 15 m/s.

the participation. There is a distinct dominance of one of the Weibull distribution. Even if the Normal distribution does give very close estimates, the contribution of the Normal distribution is insignificant. The difference in the 99 percentile estimates is less than 4%. Figure 2 shows the tail behavior of the different distributions. It can be seen that the Gumbel distribution gives the highest estimates due to the heavy tail. Weibull distribution and the Normal distribution has an overlapping tail for high fractiles.

The extrapolation from the short-term distribution of a random sea state to a long-term distribution is straightforward. The number of the sea states included in the analysis are considered to be independent and the extreme distribution for the period of one year can be calculated according to the Equation $F_{1year} = F^N$, where F= extreme flap moment

Table 3: participation factors and 100 year return values of the distribution functions of the flap moment using Bayesian analysis

Distribution	participation	100 year
Gumbel	15%	1.03
Normal	0.7%	0.93
Weibull	34.2%	1.00
Gamma	48.6%	1.01
Exponential	0 %	1.08
LogNormal	1.2%	0.94
Bayes		1.005

distribution and N = number of independent sea states. It has to be said that by carrying out the Bayesian analysis before the extrapolation, the estimate is higher than carrying out the Bayesian analysis after the extrapolation. In this case the former procedure has been chosen.

Table 2 shows also the estimates of the extreme flap moment with a return period of 100 years. It can be seen that the influence of the Gumbel distribution increases with the extrapolation and the Bayesian analysis yields practically an average between the Gumbel estimate and the Weibull estimate. The extrapolation favors the tail of the distribution, thus even with less contribution in percentage, the absolute contribution is higher because of the heavier tail. However, one should keep in mind that the estimate is always bounded by distributions that are included in the Bayesian analysis. For this reason three more distributions are added to the Bayesian analysis to determine the effect of including more heavy tailed distributions. These are the LogNormal, 3 parameter Gamma and the Exponential distributions.

Table 3 shows the participation factors of different distributions for the flap moment. The weight of the 3 parameter Weibull and Gamma distribution are the dominant one. The Weibull and Gamma distribution are strongly related to each other. Thus, the addition of the three extra distributions has not changed significantly the 100 year estimate of the flap moment. The Exponential distribution has the highest estimate, however, the Bayesian has given it a weighting factor of 0, despite the fact that the Exponetial distribution is not rejected by the goodness of fit test. Figure 3 shows the different fitted distributions to the extreme flap moment. Figure 4 shows the tail region of the fitted distributions. As can be seen the 6 distributions cover the data reasonably in the probability space.

Table 4 shows the estimate of the 100 year overturning moment (OTM) of the support structure using different distribution functions.

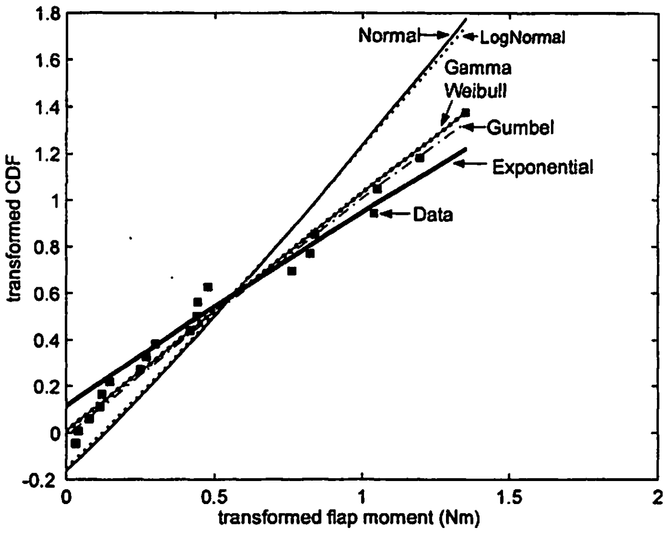


Figure 3: 6 fitted distributions of the extreme flap moment plotted in Weibull scale together with the original data.

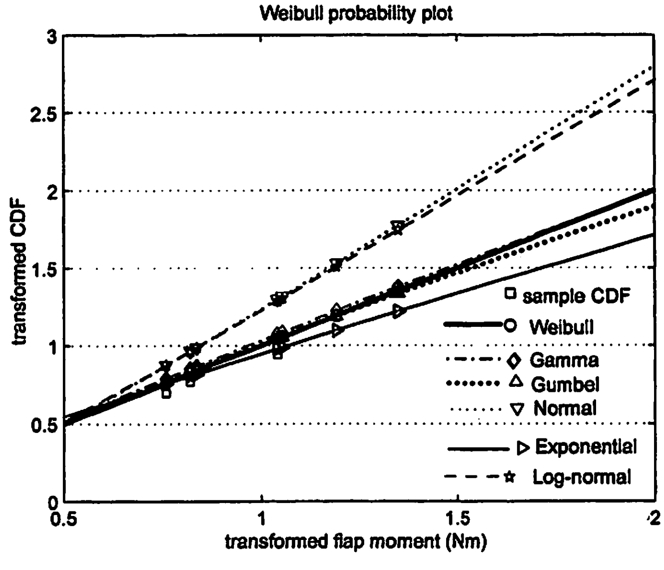


Figure 4: Tail region of 6 fitted distributions of the extreme flap moment plotted in Weibull scale together with the original data.

Table 4: participation factors and 100 year return values of the distribution functions of the overturning moment using Bayesian analysis

Distribution	participation	100 year
Gumbel	2%	1.05
Normal	0.3%	0.93
Weibull	10.3%	1.00
Gamma	86.6%	1.00
Exponential	0 %	1.12
LogNormal	0.5%	0.94
Bayes		0.997

The participation factors as result of the Bayesian analysis is also shown. The 100 year OTM is normalised with respect to the 3 parameter Weibull estimate. As can be seen, the dominance of Gamma and Weibull is very strong. The 100 year OTM is then dominated by the estimate of these two distributions.

1.3 Uncertainties in the distribution parameters

In this section we are going to examine the uncertainties of the distribution parameters. The Bayesian analysis that is applied to treat the uncertainties of the distribution parameter are given in the previous sections. We applied the method to three different distribution functions used to model the extreme flap moment, Gumbel, Weibull and the Normal distribution.

First the data likelihood function defined in the Equation 3 is obtained. The Weibull distribution has three parameters, thus the data likelihood is a function of three variables. Figure 5 shows the data likelihood for different combination of the three parameters (that is, one parameter is fixed). In principle one needs to integrate the data likelihood function over all the possible parameter values. However, the function decays rapidly toward zero, hence practically only a limited region need to be considered. The slight dependency between the two parameters σ and k can be seen by following the maximum of the likelihood function for a given location parameter u (Figure 5 top left). It seems rather symmetrical along a constant value of σ and k but actually the symmetrical axis is slightly oblique. As larger σ correspond to larger shape factor k and vice versa. For constant k and σ there is also a slight symmetry between the two parameters. As can be seen the shape factor and the scale factor decreases for increasing location factor, in this way the fitted probability of Weibull distribution does not deviate considerably from the sample probability. In return the data likelihood

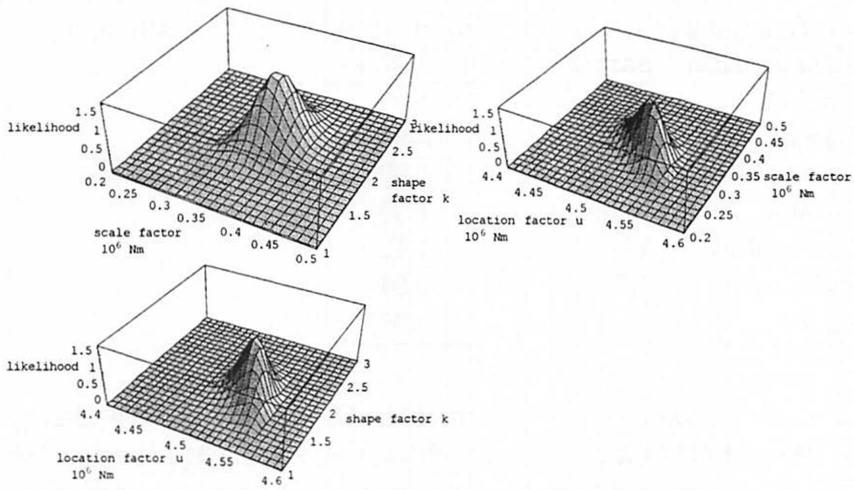


Figure 5: data likelihood function for a Weibull distribution with the extreme flap moment of 15 m/s

is higher.

First we obtain the posterior distribution of the distribution parameters In this case we assume a constant distribution of the prior and the posterior distribution is the data likelihood function with a constant normalisation factor Using the total probability theorem (Equation 4) we obtain the distribution of the extreme flap response that includes the uncertainties of the distribution parameters. Instead of determining the probability of non exceedance of a certain flap moment , it is also possible to determine the fractile values that are relevant for the design. This can be done by replacing the distribution function with the inverse of it. In this case we determine the 100 year return value of the extreme flap response.

To avoid the triple integration we split the integral of the Equation 4 in a double and a single integral. First the data likelihood function is integrated over the σ and k domain, which gives the marginal distribution of the location parameter u. Then the Equation 4 is integrated over the domain of σ and k. This yields the conditional probability (or the conditional quantile) depending on the location factor u. By applying the total probability theorem again to the conditional quantile and the marginal distribution of the location parameter we obtained the quan-

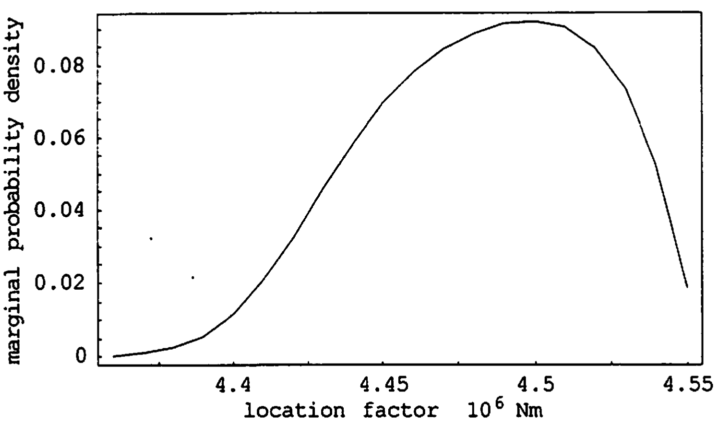


Figure 6: marginal probability density of the location factor u

tile value that takes into account the uncertainties of all the distribution parameters.

For the Weibull distribution the variation of the scale parameter and shape factor has the strongest impact on the estimate of the return values. Because the location parameter varies linearly with the physical variable ($x = u + \sigma\tilde{x}$). The shape parameter k determines the 'gust factor' and the variation of the scale factor is always augmented by the 'gust factor' factor. The difference with a variable u is less than one percent if we consider the location parameter as a constant (estimated with MLE)

We apply this procedure to the Gumbel and Normal distribution and obtain quantile values that is representative for the 100 year return value. The result are shown in the Table 5

Clearly the spreading of the parameters does not have very strong effects on the long term estimate. The difference is no more than 2% for all the distributions. This can lead to the assumption that the uncertainties of the distribution parameters do not affect considerably the long term estimate of the extreme flap response. However, one should keep in mind that the synthetic data set from simulations may present less variability than the real distribution (e.g. measurement), in that case the variability of the distribution on the long term estimate maybe more significant. In many cases one need to know only the confidence interval of the distribution parameters, which can be done with Bootstrap.

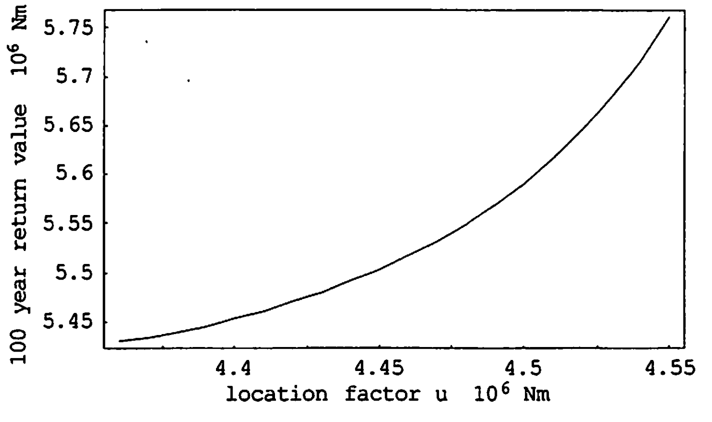


Figure 7: 100 year return estimate of the flap response conditional on the location factor u

Table 5: 100 year return values with parameter uncertainties and without

Distribution function	Bayesian estimate	Least square estimate
Weibull	$5.57{\cdot}10^6 Nm$	$5.62{\cdot}10^6 Nm$
Gumbel	$6.21{\cdot}10^6 Nm$	$6.13{\cdot}10^6 Nm$
Normal	$5.45{\cdot}10^6 Nm$	$5.43{\cdot}10^6 Nm$

1.4 What are the effects of including these uncertainties

Now we combine the result from the two previous section dealing with the uncertainties of the distribution type and the distribution parameters. The 100 year return value obtained in this manner is less than one percent different with the Weibull estimate without considering any uncertainties.

From a practical point of view one can say that analysis of the uncertainties contribute to the decision making process. The question of which distribution type to choose was made on the basis of the Bayesian analysis. The evidence of the predominance of one distribution function make it unnecessary to combine the different distributions. However, one should be aware of the fact that the data are obtained using numerical simulations. The data are more homogenous. It may not be the case for data obtained from mesurements, in such case the participation factors of the chosen distributions may become more even.

The uncertainties in the distribution parameters are less than we expected. Often uncertainty would contribute to a higher estimate of the return value, in the Weibull case the inclusion of the uncertainty lead to a lower estimate instead. This can be seen in the marginal distribution of the location parameter u.(Figure 6). The probability that the location parameter is below the location parameter estimated with the least square method is much higher. Hence the long term estimate is lower because integrating over the probability of u with the conditional quantile of the extreme response (Figure 7) yields a lower value. This has to do with the fact that the 3 parameter Weibull distribution is a limited distribution, the data likelihood for location parameter larger than the minimum value of the sample is zero, thus the marginal distribution of the location parameter has a right end point. However, the estimate depends on the conditional quantile as well, which in this case does not vary rapidly with the change of the location parameter u.

Despite the subjective elements of the Bayesian analysis One may regard the Bayesian analysis as a tool that offer a rational way of dealing with limited information with uncertainties.

References

[1] P. Cheng and G. van Bussel. A probabilistic approach to extreme loading of an offshore wind energy system. In *Proceeding of the 8th International Conference on Structural Safety and Reliability*, Los Angeles, 2001. International Association for Structural Safety and Reliability (IASSAR), IASSAR.

[2] R. D'Agostino and M. Stephens(eds). *Goodness-of-Fit Techniques.* Dekker, New York, 1986.

[3] B. Efron and R. Tibshirani. *An Itroduction to the Bootstrap.* Chapman and Hall, New York, 1993.

[4] A. Law and W. Kelton. *Simulation Modeling and Analysis.* Mc-Grawhill Inc., New York, 1991.

[5] R. Reiss and M. Thomas. *Statistical Analysis of Extreme Values.* Birhaeuser Verlag, Basel, 1997.

[6] A. Vrouwenvelder and J. Vrijling. *Probabilistisch Ontwerpen.* Delft University of Technology, Delft, 1993. Lecture Note in Ducth.

Discussion

When calibrating partial safety factors it is normal to assume the extreme structural response to follow a Type-1 (Gumbel) distribution. This assumption will normally hold for extreme loads originating from extreme wind speeds. However, for extreme response originating from extreme gust at normal wind speeds this assumption may not be true, as indicated in this paper.

By
Bo Juul Pedersen
NEG-Micon A/S
Alsvej 21, DK-8900 Randers

1. Introduction

For a modern pitch controlled wind turbine it often turns out that maximum deflection due to blade bending during normal operation compared to allowable blade – tower clearance becomes governing for the flapwise bending stiffness of the blade. A priori, it must be assumed that realisations of extreme blade deflections, u_{max}, from operation at all mean wind speed will to some extent contribute to the overall extreme-value distribution, during operation, i.e.

$$F_E(u_{\max}) = \int_{V_i}^{V_O} p(V) \cdot F_e(u_{\max}|V) dV \qquad (1.1)$$

where
- p(-) is the PDF of the mean wind speed, V, (typically assumed Rayleigh distributed)
- F_e(-) is the extreme-value distribution at mean wind speed V, (assumable to be one of the three existing asymptotically extreme-value distributions)
- V_i and V_o is cut-in and cut-out wind speeds respectively

However, it seems reasonable to assume that some mean wind speed bins will contribute very marginally to especially the upper trend of $F_E(u_{max})$, e.g. operation at low mean wind speeds. By means of the aero-elastic time-domain simulation program, Flex5, ref. [1], maximum values of the blade deflection process at different selected mean wind speeds are found and shown in figure 1.1, for a typical pitch regulated turbine.

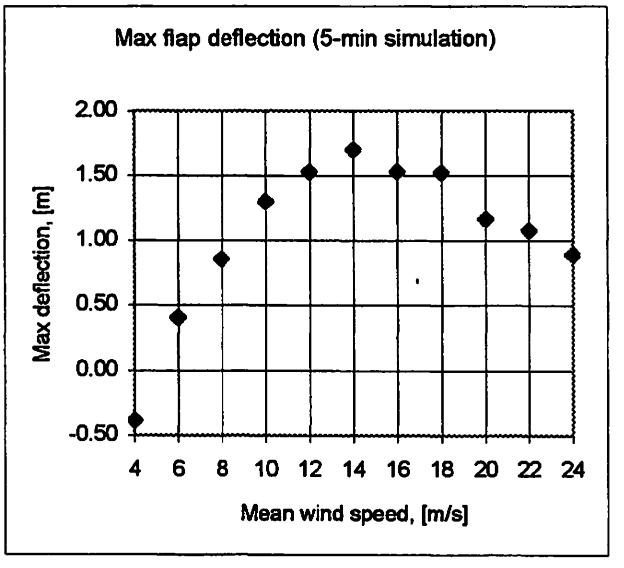


Figure 1.1 Maximums of blade deflection process at different mean wind speeds

In obtaining the data in figure 1.1, standard IEC, class A turbulence has been used in simulations of 5-min length. As seen in the figure, maximum flap deflection will occur for wind speeds around V_r, i.e. it could be expected that the deflection process around V_r would be governing for the upper trend of $F_E(u_{max})$.

2. Determination of design blade deflection

In industry it has for some years now been normal to identify the most critical mean wind speed bin and then simulate a sufficiently large number of realisations of extreme-values each from e.g. 5-min simulation. By standard extreme-value ranking, simulation results are fitted to an extreme-value type-I (Gumbel) distribution and extrapolated to a predefined time-period, e.g. 50-years, taking into account the amount of operational hours witnin the selected mean wind bin. In figure 2.1 simulated extreme-values at a mean wind speed of 14 m/s have been ranked and fitted to a Gumbel distribution. The method has in general terms been described by ref. [2].

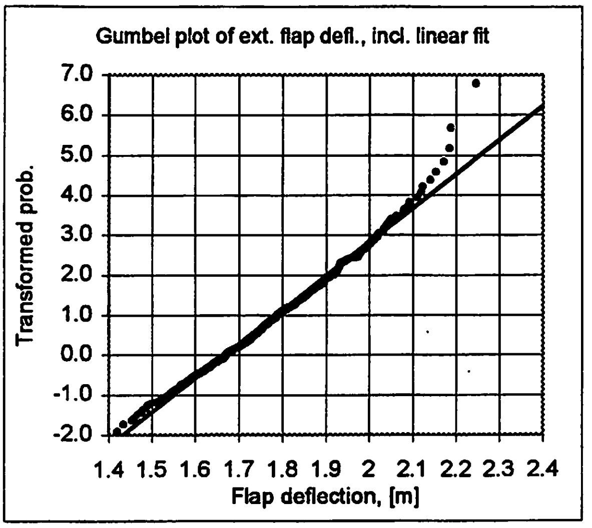


Figure 2.1 Gumbel plot of simulated extreme-values of blade deflections for operation at rated wind speed

The Gumbel CDF is given by

$$F_I(u_{\max}) = \exp\left(-\exp\left(-\frac{u_{\max} - \alpha}{\beta}\right)\right) \qquad (2.1)$$

For the linear fit in figure 2.1 one gets

α = 1.6684 m (scale)
β = 0.1172 (dispersion)

In figure 2.1 extrapolation to a 50-year value can be performed (to a transformed probability value of approx. 14.9 if $V_r \in [12\ ;16]$ m/s and IEC class I is assumed). The number of simulations which is required to obtain a sufficiently safe estimate on the 50-year value can be found by standard statistical methods. However, this is only a valid procedure if the assumption that simulated data truly follows a Gumbel distribution. Observing the very upper trend in figure 2.1 one may be sceptical that the data actually fits a Gumbel distribution. In this respect, the obtained 50-year value, based on a linear fit could perhaps be expected to be non-physical !

A simple way to address this problem is to base the Gumbel extrapolation on only the upper tail of the extreme-value data. In contrast to spectral methods for determined extreme-values, as e.g. Davenport peak-factor method, no information on the entire extreme-value distribution is required, which speaks in favour of this simple approach. However, it has the drawback that it requires a large amount of simulation data to identify the upper trend (and is this then the final trend ?).

3. Existence of an approx. deterministic maximum blade deflection limit

From figure 2.1 one could be tempted to believe that the simulated data will have a vertical asymptote, i.e. a deterministic upper limit. Two different phenomena could, dependently or independently, be expected to cause this. The first thing is that there could exist an upper limit for the maximum lift obtainable for the blade due to an assumption that amplitudes of wind gusts with rise times faster than the pitch response will be physical limited in size in a standard roughness driven boundary layer. The second thing is that the deflection process is conditioned on two, to some extent independent, processes. That is the pitch process and the wind gust process. Looking at the data in figure 1.1 the reason that u_{max} is nearly constant for wind speeds above V_r is that the gust process becomes more severe when IEC turbulence is assumed (std(V) increases for increasing V) however the pitch process is less severe and will more seldom be at a critical level around 0°.

An upper limit for the maximum lift coefficient for the naca 63-4 profiles, used to generate the data in figure 1.1, is expected to be approx. 1.35 (ignoring in-stationary lift). If one assumes max lift present in the whole length of the blade and 10 % rotor overspeed with a free wind of 25 m/s – considered as a short-time value with pitch angles of 0-deg corresponding to a mean wind speed of 14 m/s, the following flap deflection is obtained

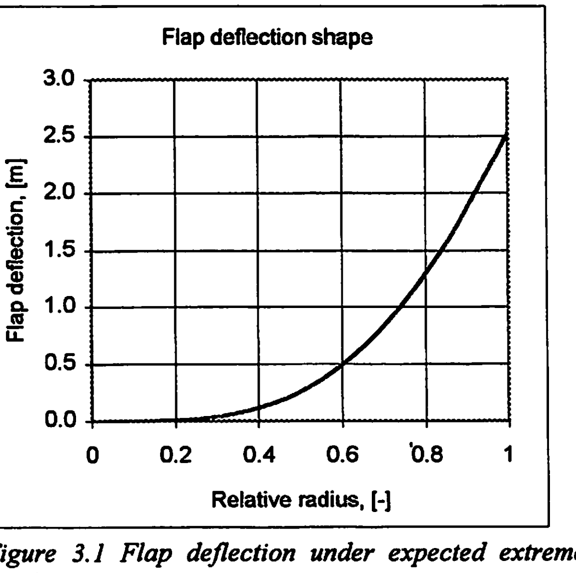


Figure 3.1 Flap deflection under expected extreme conditions

- with a max value of 2.53 m

4. Fitting data to a type-III CDF

If the 2.53 m is considered to be a (pseudo) deterministic maximum for stochastic realisations of extreme flap deflection one needs to fit these to a CDF different from the Gumbel.

A extreme-value distribution type III seems to be a good chose. This is given by

$$F_{III}(u_{\max}) = \exp\left(-\left(\frac{U_{\max} - u_{\max}}{U_{\max} - U_n}\right)^k\right) \quad (4.1)$$

where $U_{max} = 2.53$ m
$U_n = 1.665$ m
$k = 5.7$

yields the fit to simulated data as given in figure 4.1

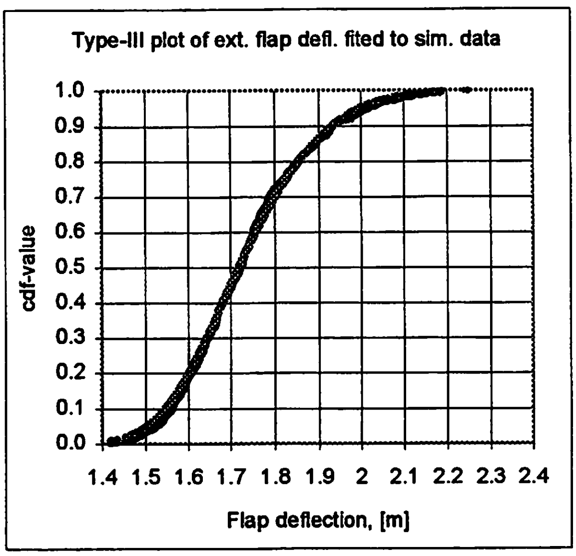


Figure 4.1 Fitting sim. data to Type-III CDF

Figure 4.2 compares the PDF for the fitted type-I and type-III

It is not believed that whether or not to use the type-III or the type-I should be based on statistical test of the goodness of the fit. Instead one has to address the physics in extreme wind gusts and the aerodynamic loading of the blade to decide which CDF to use.

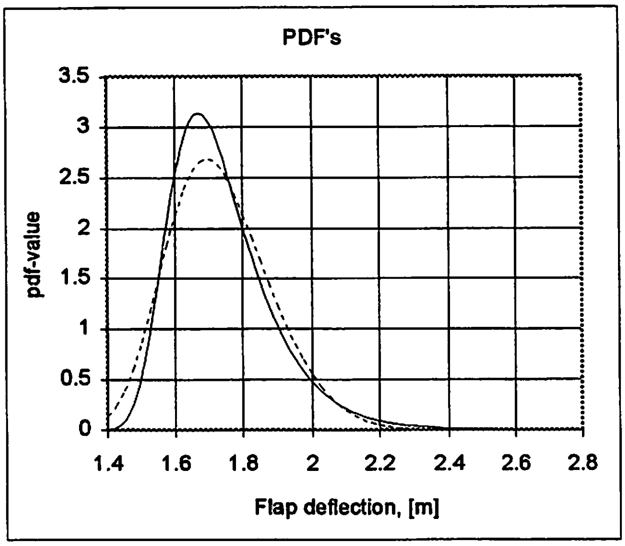


Figure 4.2 PDF for type I and III (dotted) fitted to simulated data

In figure 4.2 the type III PDF of course stops at 2.53 m.

5. Impact on partial safety factor

If there exists an almost deterministic upper limit for the blade deflection this will off course have impact on the determination of a partial safety factor for blade-tower interaction. An extreme flap deflection of 2.53 m can under the type-I assumption be found to have a return period of 1/20 year, i.e. approx. 18 days.

If the wind conditions causing a blade deflection of 2.53 m can be determined to have a return period less than 50 years, and the type-III assumption is used, the 2.53 m could be considered as a 50 year value and the corresponding partial safety factor should in principle be equal or at least close to unity.

References :

[1] Flex5, Aeroelastic simulation program by Stig Øye, AFM, DTU

[2] "Statistical analysis of wind turbine rotor tower clearance", D.J. Lanio, Windward Engineering, AIAA-2001-0048

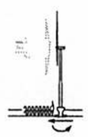
Extremes During Operation

Niels Jacob Tarp-Johansen
Sten Frandsen
Peter Hauge Madsen

Outline

- Rødsand
  - Issues
  - Method
  - Results
- Other work
  - Peak value distribution (Patrick Moriarty)
  - Design turbulence (Sten Frandsen)

Rødsand, Issues



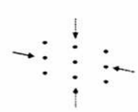
- Do wakes dominate?
- Is one mean wind speed bin sufficient?

Rødsand, Method

$$F_{mix}(m_{max}) = 1 - \frac{1}{N}$$

$$F_{mix} = p_1 F_{m,1} + p_2 F_{m,2} + p_3 F_{m,3}$$

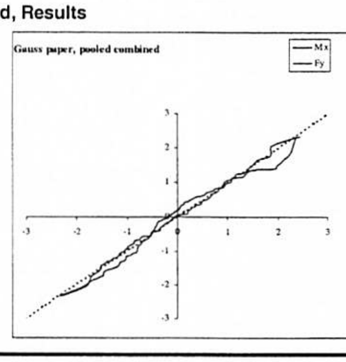
$$m_{max} = F_{m,3}^{-1}(1 - \frac{1}{p_3 N})$$



Rødsand, Method

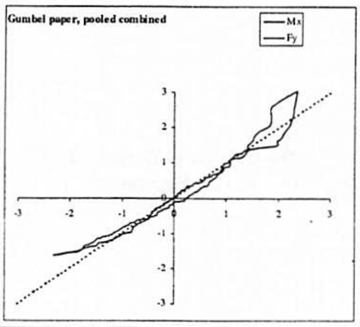
- 10-min extreme response – not turbulence intensity
- Conditional on mean wind
- Simulating conditional on *I*
- Only one sea-state
- Including mean wind.
- Sten Frandsen's Wake turbulence models based on Vindeby.

Rødsand, Results



RISØ

Rødsand, Results

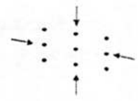


RISØ

Rødsand, Results

Run simulations, estimate distribution parameters, and solve for max.

	NS-wake	All
M_x	49.1	49.8
F_y	1.17	1.22

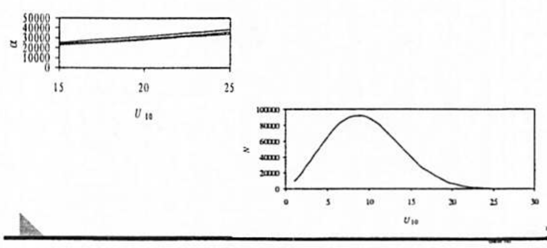


RISØ

Rødsand, Results

- Including mean wind, minor effect 5-10%

$\sqrt{\log(N)}$



RISØ

Other work

- Peak Value Distribution
  - Why? / Why not.
- Design turbulence
  - Why? / why not.
  - Quasti-static

RISØ

TC88

Wind Turbine Systems

Peter Hauge Madsen

Slide no.

RISØ

Publications issued by TC 88

IEC 61400-1 Ed. 2.0 E
Wind turbine generator systems - Part 1: Safety requirements

IEC 61400-2 Ed. 1.0 B
Wind turbine generator systems - Part 2: Safety of small wind turbines

IEC 61400-11 Ed. 1.0 E
Wind turbine generator systems - Part 11: Acoustic noise measurement techniques

IEC 61400-12 Ed. 1.0 E
Wind turbine generator systems - Part 12: Wind turbine power performance testing

Slide no.

Publications issued by TC 88

RISØ

IEC 61400-13 TS Ed. 1.0 E
Wind turbine generator systems - Part 13: Measurement of mechanical loads

IEC 61400-23 TS Ed. 1.0 E
Wind turbine generator systems - Part 23: Full-scale structural testing of rotor blades

IEC WT 01 Ed. 1.0
IEC System for Conformity Testing and Certification of Wind Turbines
Rules and procedures

Slide no.

TC88 Work Programme

RISØ

IEC 61400-3 Ed. 1.0	ANW	88/123/NP	00-06	00-06	01-12	
WGs : 03			Project Leader : D. Quarton			

Wind turbine generator systems - Part 3: Design requirements for offshore wind turbines

IEC 61400-11 Ed. 2.0	ADIS	88/141/CD V		01-10	02-04	
WGs : MT 11			Project Leader : H. Klug			

Wind turbine generator systems - Part 11: Acoustic noise measurement techniques

IEC 61400-21 Ed. 1.0	CDIS	88/144/FDIS	95-10	01-09	01-11	02-01
WGs : 21			Project Leader : J. Tande			

Wind turbine generator systems - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines

IEC 61400-24 TS Ed. 1.0	APUB	88/128/CD V	98-02	01-04	01-06	
WGs : 24			Project Leader : P. Christiansen			

Wind turbine generator systems - Part 24: Lightning protection for wind turbines

Slide no.

TC88 Work Programme

RISØ

IEC 61400-25 Ed. 1.0	ANW	88/136/N P	01-03	01-03	02-10

WGs : 25 Project Leader : M. A. Johnsson
Wind turbines - Communication standard for remote control and monitoring of wind power plants

PNW 88-147 Ed. 1.0	PNW	88/147/N P		01-09	02-02

WGs : PT Project Leader : Dr.P Gardner
Wind Turbines - Electromagnetic Compatibility

PNW 88-148 Ed. 1.0	PNW	88/148/N P		01-09	02-02

Project Leader : D. Helmut Klug
Declaration of sound power level and tonality values of wind turbines

Slide no.

IEC TC88 MT1 - Structural reliability

RISØ

- Safety factor calibration
- Application of partial safety factors in dynamic simulation
- Extrapolation of loads

Slide no.

Summary of meeting

Structural reliability is presently an area in wind turbine design that draws attention from many different interest groups. Manufactures are looking for reliable methods to design larger and more optimised wind turbines in a safe way. Research institutes and universities are currently involved in activities aiming at developing and refining basic tools within the field. Standardisation bodies, such as IEC, are putting great emphasis on developing rules and regulations in the area.

As a result of this common interest, the symposium attracted 15 participants from universities, research institutes, classification bodies and industry giving 11 presentations covering different aspects of the theme of the symposium. Each of the presentations is briefly summarised below:

Gunner C. Larsen (Risø): Structural Reliability of Wind Turbines - An Introduction.

In the design of wind turbine structures, ultimate loading as well as fatigue loading is addressed. The design process involves aeroelastic modelling of the wind turbine as well as specification of appropriate load scenarios. In addition to uncertainties associated with load and resistance, both the structural modelling, the aerodynamic modelling and the load modelling may be encumbered with uncertainty. These uncertainties all have an impact on the safety against structural failure. Traditionally the involved uncertainties can be categorised into different disjoint classes:

Natural variability. This is uncertainty associated with a random character inherent in the physics of a system. Related to wind turbine design, straight forward examples are stochastic wind loading caused by turbulence, stochastic wave loading and variability in material resistance. Natural variability is a type of uncertainty, which cannot be reduced.

Model uncertainty. This class of uncertainties relates to the choice of deterministic as well as stochastic models applied in the design computations. Generally speaking, the model uncertainty is caused by insufficient knowledge/ability or selected simplifications in the mathematical formulation of the physical system. The model specification is a crucial step that might be responsible for a substantial amount of uncertainty – for example the well known "tail sensitivity" of reliability computations. Model uncertainty can be reduced by using a better model.

Statistical uncertainty. Statistical uncertainty is closely associated with a limited amount of available data. It manifests itself as uncertainties in the relevant parameter estimates. Statistical uncertainty can be reduced by increasing the amount of data, e.g., by further sampling.

Structural reliability analysis constitutes the synthesis of the above listed sources of uncertainty into a measure of the probability of survival for the structure, and such analyses can further be condensed into structural design codes by so called partial safety factor calibration.

Gunner C. Larsen and Anders M. Hansen (Risø): Uncertainty in Design Loads.

There is an obvious interest in quantifying the magnitude of uncertainty associated with design loads as established based on traditional aeroelastic computations. The present presentation deals with this topic.

Based on a number of simplifying assumptions, an analysis of the uncertainty on the *design fatigue loading*, of a modern active stall regulated 2 MW wind turbine (in normal operation), have been conducted. Model uncertainty is neglected, and only the statistical uncertainty and the natural variability, on four vital input parameters (i.e. design turbulence intensity, aerodynamic lift- and drag parameters and the intercept in a S-N curve fatigue formulation), are taken into account in the analysis. The analysis has been performed for both an onshore- and an offshore siting situation. In both cases, load specifications from the IEC 61400-1 code have been adopted.

The following conclusions emerge from the analysis:

- Uncertainty in the material (fatigue) properties is a dominating factor. However, as it is caused (mainly) by natural variability it can not be substantially reduced unless different materials are introduced;
- Uncertainty in predicted lifetime, caused by uncertainty in the design turbulence intensity as well as in lift- and drag coefficients, is also significant - these can be reduced by increasing the number of observations/predictions and improving the methods for predicting the aerodynamics coefficients;
- The resulting uncertainty is *not* additive in the selected four uncertainty factors.

Gunner C. Larsen (Risø): Statistical Uncertainty in Design Turbulence Intensity - An Analytical Approximation.

The atmospheric turbulence has a major effect on the fatigue design of wind turbine structures. Of the parameters characterising the atmospheric turbulence, the turbulence intensity is the most important in this respect. The uncertainty associated with this quantity is therefore of interest in relation to reliability assessment of wind turbine designs.

The present work presents a model that quantify the statistical uncertainty on the design turbulence intensity in terms of a probability density function. The model is based on the conventional formulation of the design turbulence intensity (i.e. a sum of the mean turbulence intensity and a factor times the standard deviation on the turbulence intensity). The model relies on a simplifying assumption on the "parent" distribution type, and it is expressed on closed form, with the number of independent statistical degrees of freedom as the only parameter. Using the model, it has been demonstrated, that the uncertainty on the design turbulence intensity tend to decrease with increasing mean wind speeds, and tend to decrease with increasing sample size (as expected).

Luc Rademakers and Henk Braam (ECN): Structural Reliability and Design Methods.

The use of structural reliability methods is fairly new within wind turbine design, but an increasing interest for this technical discipline has been recognised in the field. The present work describes the past and present Dutch activities in the area.

The introduction of structural reliability methods in the wind turbine industry requires both that the methods are further developed and made available for manufactures, and that the design codes are adjusted to also include this design philosophy (f.x. specification of target values for reliability). To support development structural reliability methods in the field, ECN has in the past been involved in two Joule III projects. The Prodeto project aimed at a calibration of partial safety factors for blade fatigue loading as well as for blade ultimate loading, whereas the Profar project dealt with the scatter in blade fatigue properties. It emerged from these projects that it is very complicated to develop complete probabilistic design methods for blade manufactures, among others, due to a number of complex failure mechanisms (fatigue, failure of the bonding line, buckling, failure of the spar, etc.) in connection with complex material behaviour of composite materials. For the support structure of offshore sited wind turbines, the introduction of probabilistic methods is more straight forward, because the offshore industry already have experience in utilising these methods and because of more simple material behaviour. As the need at the same time is believed to be higher, the Dutch efforts on the field are presently devoted to offshore support structures.

Niels Jacob Tarp-Johansen (Risø): Extreme Loads During Operation.

Currently an effort is made in the area of extrapolation of normal operational load effects to lifetime extremes. The interest in this area is motivated by the fact that extrapolated load effects are in current design comparable to, or even larger than, standstill loads. The work presented regarded a numerical study of the extreme loads in a wind farm in which the presence of neighbouring turbines increase the ambient turbulence level and induces wakes with especially high turbulence. It has been shown that in a rectangular grid configuration where the spacing in the one direction is somewhat smaller than in the other direction, it suffices to consider only the loads induced be the wakes in the first direction. The work was based on Sten Frandsen's formulas for wake effects, assuming essentially that characterising the increased turbulence by an increase in turbulence intensity solely is sufficient, and extrapolation of Gumbel distributions fitted to simulated 10.-min-extremes. Others have instead considered the peak distributions to which they have fitted quadratic Weibull distributions. Taking statistical uncertainty into consideration it is disputable what approach is the better. The numerical study included the consideration of more mean wind speeds. It turned out that a few mean wind speed bins around the bin with the highest 10.-min. extreme response gives the main contribution to the extrapolated lifetime extreme.

Niels Jacob Tarp-Johansen, Peter Hauge Madsen & Sten Frandsen (Risø): Introduction to Debate on Reliability Level of Wind Turbines.

In connection to the revision of the IEC standard 61400-1: Wind Turbine Generator Systems - Part 1: Safety Requirements, 2nd Ed. a simplified probabilistic safety factor calibration is carried out. Present safety factors have been adopted from existing structural design codes ranging over many different types of structures and a wider set of load cases than relevant to wind turbine engineering. What is offered is a wind turbine specific calibration leading to safety factors optimal for wind load dominated structures. The following issues have been dealt with:

- extreme loads and extreme loads during operation (i.e. currently not fatigue loads)
- reliability level
- differentiation of safety factors with respect to load model uncertainties
- statistical simulation uncertainties, and
- weighting of safety factors with respect to the ratio of aerodynamic loads to gravity loads in a given cross-section.

Of central importance in the work is the choice of model uncertainties. The choice of uncertainty model for shape factors was discussed. It showed that that there are differences between interpretations of shape factor uncertainties in structural engineering and wind turbine engineering.

John Dalsgaard Sørensen (Aalborg University): Calibration of Partial Safety Factors and Eurocodes.

The main parts of the Danish structural code system (Basis of design, Action and Loads, Concrete, Steel, Timber, Masonry and Foundation) have been revised in the period 1996-1999. The paper describes the main steps in the probabilistic code calibration performed in order to obtain the optimized partial safety factors in these new Danish Structural Codes (1999). First, the reliability level is evaluated for a number of typical, simple structures designed according to the previous Danish Structural Codes (1982) with a stochastic model for the uncertain action and structural variables relevant for Danish conditions. The reliability analyses show a non-uniform reliability level for different materials and actions. Next, new partial safety factors in a slightly modified code format are calibrated such that the average reliability level is the same in the new codes as in the previous codes, i.e. the average reliability level in the previous structural codes is used as the target reliability level. Using the optimized partial safety factors, a more uniform reliability level is obtained for different types of materials / structures and for different types of actions.

The reliability level is discussed in relation to a severe storm in December 199 in Denmark, where wind speeds slightly larger than the level of the characteristic value were measured. The observed structural damages and the lack of damages on structures designed in accordance with the Danish structural codes are used as basis for a discussion of the target reliability level to which the partial safety factors were calibrated.

Combinations of variable actions are not part of the calibrations carried out.

The code format and partial safety factors in the Danish structural code are compared to those in 'Basis of Structural Design', Eurocodes (2001). Compared to the Danish code, the Eurocodes give a much more non-uniform distributed safety level as function of material type and loading type. Finally the main structure in the new Eurocode for wind actions was presented.

Peter Hauge Madsen (Risø): IEC Standardisation.

IEC is an international organisation dealing with standardisation within all fields of electrotechnology. The IEC's standards are vital since they represent the core of the World Trade Organization's Agreement on Technical Barriers to Trade (TBT).The standardisation work in IEC is organised in a number of Technical Committee's (TC's), each representing a specific electrotechnical field.

The present contribution deals with the ongoing standardisation efforts in TC88 covering the field of Wind Turbine Systems. To draft documents for new standards, TC88 sets up a project team, while for modifying standards, it sets up a maintenance team. Each are composed of a limited number of experts appointed by the members of the committee. Presently, a maintenance team - MT14 - is working on a general revision of standard IEC 61400-1 WTGS – Part1: Safety Requirements, 2nd edition. In particular, MT14 shall consider the limitations in the present standard in relation to installations offshore, in wind farms and/or in complex terrain. Having completed its task the MT14 team will be disbanded, and the prepared documents will be submitted to the National Committees for voting with a view to their approval as international standards. IEC's international standards are reached by international consensus among the National Committees.

Knut O. Ronold (Det Norske Veritas): Statistical analysis of simultaneous wave and wind climate data

As an introduction, a brief presentation was given of DNV's recent activities with respect to probabilistic analysis of wind turbines. Subsequently, emphasis was given to presenting results from statistical analysis of simultaneous wave and wind climate data. The basis for the analysis consists of simultaneous wave and wind data obtained at two Danish offshore locations in 1999 and 2000. The following climate variables were considered:

- Significant wave height
- Zero-upcrossing period for waves
- 10-minute mean wind speed
- standard deviation of wind speed

The statistical analysis was used as a basis for stochastic modelling – in terms of probability distributions – of these wave and wind climate variables as needed in probabilistic analysis of wind turbines. A scheme was presented by which one of the variables is modelled as an independent variable and each of the other variables is modelled as a dependent variable whose distribution parameters are functions of the independent variable and/or one of the other dependent variables. Generic distribution models suitable for representation of the distributions were identified and distribution parameters were estimated by fitting to the data.

Bo Juul Pedersen (NEG_Micon): Estimation of Ultimate Flapwise Deflection.

For a modern pitch controlled turbine, the ultimate flap-wise deflection is often controlling the design of the blade structural flap-wise stiffness. This is due to requirements related to the blade/tower clearance. The work presented deals with estimation of this parameter.

Traditionally, a Type-1 Gumbel distribution has been fitted to such extreme deflections as obtained from numerous aeroelastic simulations of an identified "most critical" mean wind speed situation. However, the computations indicate that the ultimate deflection may have an asymptotic upper limit. Two different phenomena could, dependently or independently, be responsible for this phenomenon. Firstly, there might exist an upper limit for the maximum lift obtainable for the blade, due to an assumption that amplitudes of wind gusts, with rise times faster than the pitch response, will be physical limited in size in a standard roughness driven boundary layer. Secondly, the deflection process is conditioned on two, to some extent independent, processes - the pitch process and the wind gust process. The observed asymptotic upper limit in turn make the Type-1 Gumbel fit deviate in the upper tail. This misfit can be circumvented by replacing the Type-1 Gumbel with an extreme-value distribution type III.

Po-Wen Cheng (TU Delft): Bayesian Analysis Applied to Statistical Uncertainties of the Extreme Responses Distribution of an Offshore Wind Turbine.

Extreme loading of wind turbines have obtained increasing attention in resent years. The work presented considers the statistical uncertainties related to extreme response distributions. The extreme responses in question are the flap moment at the blade root and the overturning moment of the support structure of an offshore wind turbine situated in the North sea. The statistical uncertainties treated here are the uncertainties concerning the choice of distribution and uncertainties concerning the distribution parameters. The uncertainties are treated with Bayesian analysis. The inclusion of the uncertainties has only marginal effect for the long-term estimates of the extreme responses when non informative priors for the distribution parameters are used. The inclusion of uncertainties may have larger effect for real measurement data.

Discussion

At the finalising discussion at the meeting there was a common interest to proceed with information exchange in this area in the future. An Ad Hoc group was sent up in order to formulate a proposal for an annex dealing with structural reliability. The following persons volunteered to participate in the group. Dick Veldkamp, Luc Rademakers, Gunner Larsen, Peter Hauge Madsen, Niels Jacob Tarp-Johansen, John Dalsgaard Soerensen and hopefully someone from NREL.

The following issues was identified as important for further consideration:

1. External conditions (parameter estimation etc.)
2. Partial safety factor calibration
3. Application of partial safety factors in dynamic simulation
4. Extrapolation of loads
5. Assessment of relevant uncertainties
6. Stochastic modelling of uncertainties
7. Limit states (fatigue, ultimate)
8. Material strength models
9. Target reliability level
10. Case studies and comparisons with good examples
11. Code format (which partial safety factors etc.)
12. Onshore and offshore

Deliverables:

1. Recommended Practice
   - code format
   - partial safety factors
   - methods for adjustment of safety factors
2. Annual workshops

Proposed title: Structural safety of Wind Turbines

Time frame: 2 - (3) years

The intention was to be able to present a proposal for a new Annex at the next Executive Committee meeting in Germany April 2002. This implies that the proposal must be ready for distribution to the ExCo secretary mid March.

List of participants

IEA R&D Meeting on Structural Reliability of Wind Turbines

Risoe, Denmark, November 2001

No	NAME	COMPANY	ADDRESS 1		ADDRESS 2	COUNTRY	CC	PHONE	E-mail
1	Bernt Pedersen	LM Glasfiber	Customer Support	Rolles Möllevej 1	DK-6640 Lunderskov	Denmark	45	79840285	bep@lm.dk
2	Bo Juul Pedersen	NEG Micon	R&D	Alsvej 21	DK-8900 Randers	Denmark	45	87 105 404	bjp@neg-micon.dk
3	Dick Veldkamp	NEG Micon DOWEC	Regulierenrind 12d		3981LB Bunnik	The Netherlar	31	306560633	dve@dowec.nl
4	Flemming Rasmussen	Risoe	Wind Energy	P.O. Box 49	4000 Roskilde	Denmark			flemming.rasmussen@risoe.dk
5	Gunner Larsen	Risoe	Wind Energy	P.O. Box 49	4000 Roskilde	Denmark	45	46 77 50 56	gunner.larsen@risoe.dk
6	Henk Braam	ECN Wind Energy	P.O. Box 1		1755 ZG Petten	The Netherlar	31	224 56 4657	braam@ecn.nl
7	John Dalsgaard Soerensen	AAU	Sohngaardsholmsvej 57		DK-9000 Aalborg	Denmark			i6jds@civil.auc.dk
8	Knut Ronold	Det Norske Veritas	Veritasveien 1		N-1322 Hövik	Norge			knut.ronold@dnv.com
9	Leo Thesbjerg	Vestas Wind Systems A/S	R&D Dept.	E.F. Jacobesens Vej 7	DK-6950 Ringköping	Denmark	46	96 75 13 80	LT@vestas.dk
10	Luc Rademakers	ECN Wind Energy	P.O. Box 1		1755 ZG Petten	The Netherlar	31	224564943	rademakers@ecn.nl
11	Maria Pia Repetto	University of Genoa	DISEG	Via Montallegro 1	16145 Genoa	Italy	39	0103532384	repetto@diseg.unige.it
12	Niels Jacob Tarp-Johansen	Risoe	Wind Energy	P.O. Box 49	4000 Roskilde	Denmark	45	46775078	niels.jacob.tarp-johansen@risoe.dk
13	Peter Hauge Madsen	Risoe	Wind Energy	P.O. Box 49	4000 Roskilde	Denmark			peter.hauge@risoe.dk
14	Po Wen Cheng	Technical University of Delft	Section Wind Energy	Stevinweg 1	2628 CN Delft	The Netherlar	31	152782073	P.W.Cheng@ct.tudelft.nl
15	Sven-Erik Thor	FOI	Aeronautics FFA	Dept of Wind Energy	17290 Stockholm	Sweden	44	55 50 4370	trs@foi.se
Cancancellation									
17	Paul S. Veers	Sandia National Lab.	Albudquerque		NM 87185-0708	U.S.A.	+1	505 844 5522	psveers@sandia.gov
18	Pat Moriarty	NREL	1617 Cole Boulevard	Golden	Col 80401	U.S.A.	1		
4	Don van Delft	Delft University	Section Wind Energy	Stevinweg 1	2628 CN Delft	The Netherlands			D.R.V.vandelft@citg.tudelft.nl
Documentation to									
	Ingemar Carlen	IC							
	Hans Ganander	TG							
	Bengt Göransson	Scanwind							
	Anders Björck Tomas Lymer	NWP							
	Lasse Bergdahl	Chalmers							
	Jenny Trumars	Chalmers							

Participants

IEA Topical Expert Meeting on Structural Reliability of Wind Turbines