



BSI Standards Publication

Wind energy generation systems

Part 9: Probabilistic design measures for wind turbines

National foreword

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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TECHNICAL SPECIFICATION

**Wind energy generation systems -
Part 9: Probabilistic design measures for wind turbines**



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CONTENTS

FOREWORD	5
1 Scope	7
2 Normative references	7
3 Terms, definitions, symbols and abbreviated terms	7
3.1 Terms and definitions	7
3.2 Symbols and abbreviated terms	10
3.2.1 Symbols	10
3.2.2 Abbreviated terms	12
4 Principal elements	13
4.1 General	13
4.2 Minimum reliability level and component classes	14
4.3 Limit states	14
4.4 Data validity	15
5 Uncertainty representation and modelling	16
5.1 General	16
5.1.1 Uncertainties	16
5.1.2 Types of uncertainty	16
5.1.3 Interpretation of probability and treatment of uncertainty	16
5.1.4 Probabilistic model	17
5.1.5 Uncertainties for wind turbines	18
5.2 External condition uncertainty modelling	19
5.2.1 General	19
5.2.2 Wind conditions	19
5.2.3 Normal wind conditions	20
5.2.4 Other conditions	21
5.2.5 Electrical network conditions	22
5.3 Load uncertainty modelling	23
5.3.1 General	23
5.3.2 Aeroelastic model	23
5.3.3 Extreme loads	24
5.3.4 Fatigue loads	25
5.4 Structural resistance uncertainty modelling	25
5.4.1 General	25
5.4.2 Geometrical properties	25
5.4.3 Material properties	25
5.4.4 Resistance models	26
5.4.5 Fatigue strength and damage accumulation	26
6 Performance modelling	26
6.1 General	26
6.2 Structural performance of primary structures	26
6.2.1 General	26
6.2.2 Load performance calibration for ultimate limit states	27
6.2.3 Evaluation of serviceability limit states	30
6.3 Performance of primary mechanical and electrical components	30
6.3.1 General	30
6.3.2 Requirements for mechanical components	31

6.3.3	Serviceability limit states for mechanical components	31
6.3.4	Requirements for electrical components and control and protection systems	31
6.4	Robustness	32
7	Assessment of reliability	32
7.1	Overview	32
7.1.1	General	32
7.1.2	Reliability measures	32
7.1.4	Accuracy requirements	34
7.1.5	Sensitivity analysis	34
7.2	Reliability-based method	35
7.2.1	General	35
7.2.2	Probability of failure for extreme design situations	35
7.2.3	Probability of failure for fatigue design situations	35
7.2.4	Updating probability of failure using test or inspection data	36
7.3	Semi-probabilistic method	36
7.3.1	General	36
7.3.2	Representative and characteristic values	36
7.3.3	Partial factor method for extreme and fatigue design situations	37
7.3.4	Reliability-based calibration of partial safety factors	37
8	Site suitability analysis	37
8.1	General approach and scope	37
8.2	Reliability models for site suitability analysis	38
8.2.1	General	38
8.2.2	Load models for site suitability assessment	39
8.2.3	Resistance model for site suitability assessment	40
8.2.4	Structural performance on site specific conditions	41
8.3	Site specific uncertainty modelling	41
8.3.1	General	41
8.3.2	Quantification of site-specific uncertainties	45
8.4	Reliability assessment	46
Annex A (informative)	Uncertainty quantification	47
A.1	General	47
A.2	Bayesian methods	47
A.2.1	General	47
A.2.2	Closed form solutions for parameter estimation	48
A.2.3	Exact inference for continuous parameters	51
A.2.4	Sampling-based inference	51
A.2.5	Exact inference for discretized parameters	51
A.3	Maximum likelihood	51
A.4	Model uncertainties	52
A.4.1	General	52
A.4.2	Example: Model uncertainty quantification	54
Annex B (informative)	Inverse FORM	63
Annex C (informative)	Example calculations for reliability assessment	67
C.1	General	67
C.2	Ultimate limit state	67
C.2.1	Design equation	67

C.2.2	Limit state equation	67
C.2.3	Reliability assessment	68
C.2.4	Direct reliability-based design	69
C.2.5	Reliability-based calibration of partial safety factors	69
C.2.6	Assess the accuracy of the computation and perform sensitivity studies	70
C.3	Fatigue limit state	71
C.3.1	General	71
C.3.2	Limit state equation	72
C.3.3	Reliability-based calibration of partial safety factors	74
Annex D (informative)	Formulation of event driven design load cases	76
D.1	General.....	76
D.2	Formulation of wind conditions with conditional events (Example DLC 2.3)	76
D.3	Probability of failure for independent events (Example DLC 2.1)	77
Annex E (informative)	Updating of distributions based on evidence.....	79
E.1	Updating of distributions for basic variables	79
E.2	Event updating.....	80
Annex F (informative)	Example of the relative approach to site suitability assessment	81
Annex G (informative)	Uncertainty scenarios for site specific wind assessment	83
Bibliography.....		87

Figure 1 – Application of a mathematical model to estimate an output based on a given input	16
Figure 2 – Typical flow chart and uncertainties to be considered in probabilistic design of wind turbine components	18
Figure 3 – Typical split between uncertainties which should be propagated through the aeroelastic model (shaded) and those which should be represented by model uncertainty	24
Figure 4 – Measures of reliability computation of failure probability.....	33
Figure 5 – Highlight of relevant uncertainties related to site suitability assessment	42
Figure A.1 – Graphical representation of the structure for estimation of a) the mean value of X when the population variance is known and b) the mean value and the variance of X	48
Figure A.2 – Plot for estimation of model uncertainty	53
Figure A.3 – Experiment value Y as function of theoretical value $h(x)$	55
Figure A.4 – Cumulative distribution and probability density functions for the predictive distribution, the estimated lognormal distribution and the predictive distribution for $n = 5$	57
Figure A.5 – Various approaches for MCMC models for model uncertainty quantification	58
Figure A.6 – Probability density function for each method	61
Figure A.7 – Cumulative distribution function for each method	61
Figure A.8 – Lower tail of the cumulative distribution function for each method	62
Figure A.9 – Lower tail of the cumulative distribution function for each method for a sample size $n = 50$	62
Figure B.1 – Contour line for ETM in the u -space and the linear approximation used in IFORM.....	65
Figure B.2 – Contour lines for ETM, linear approximation (in the u -space), and the characteristic values defined in IEC 61400-1	66

Figure C.1 – Yearly (conditional) probability of failure for the calibration example with $COV_{gen} = 20,0 \%$ and $\gamma_R = 1,35$	75
Figure C.2 – Yearly (conditional) reliability index for the calibration example with $COV_{gen} = 20,0 \%$ and $\gamma_R = 1,35$	75
Table 1 – Minimum reliability requirements	14
Table A.1 – Theoretical and experimental values	54
Table A.2 – Stochastic model.....	58
Table A.3 – Parameters and moments estimated using each method	60
Table A.4 – Selected quantiles for the predictive distribution (including statistical/parameter uncertainty) and the fitted lognormal distribution (not including statistical/parameter uncertainty) using each method	60
Table C.1 – Baseline stochastic variables for load and resistance model	68
Table C.2 – Annual reliability index for different main wind turbine components (tower) and design situations (DLC 1.3 and 6.1)	69
Table C.3 – Resulting reliability index for different values of design parameter for simplified example	69
Table C.4 – Resulting reliability for different partial safety factor for loads (given $\gamma_M = 1,2$)	70
Table C.5 – Assessment of reliability index convergence with number of draws in Monte Carlo simulations	70
Table C.6 – Sensitivities of the reliability index with respect to each random variable in the limit state equation.....	71
Table C.7 – Baseline stochastic model for the fatigue limit state analysis	73
Table C.8 – Results for safety factor calibration exercise under different assumptions of COV_{gen}	74
Table F.1 – Stochastic model.....	81
Table G.1 – Uncertainty scenarios for anemometer calibration.....	83
Table G.2 – Uncertainty scenarios for mounting effects of anemometers	83
Table G.3 – Uncertainty scenarios for measurement heights.....	83
Table G.4 – Uncertainty scenarios for amount of available data	84
Table G.5 – Uncertainty scenarios for long-term wind speed distribution.....	84
Table G.6 – Uncertainty scenarios for extreme wind speed events.....	84
Table G.7 – Uncertainty scenarios for terrain map quality	84
Table G.8 – Uncertainty scenarios for wind shear modelling	85
Table G.9 – Uncertainty scenarios for terrain complexity.....	85
Table G.10 – Uncertainty scenarios for distance from measurement point to position of interest	85
Table G.11 – Uncertainty scenarios for wake models	85
Table G.12 – Representative values of COV of wind parameters for normal scenario.....	86

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**Wind energy generation systems –
Part 9: probabilistic design measures for wind turbines**

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The text of this Technical Specification is based on the following documents:

Draft	Report on voting
88/1063/DTS	88/1102/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available

at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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- reconfirmed,
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1 Scope

The part of IEC 61400, which is a Technical Specification, sets out minimum requirements to the use of probabilistic design measures in order to ensure the structural and mechanical integrity of wind turbines. The document is based on the general approach in ISO 2394, which also forms the basis for IEC 61400-1. In 61400-1, the design verification approach is based on deterministic design using safety factors. However, edition 4 of IEC 61400-1:2019 opens for introduction of probabilistic design in an informative annex specifying requirements to the calibration of structural material safety factors and structural design assisted by testing. IEC 61400-1 is the governing standard. This document provides appropriate methodologies and requirements for full probabilistic design by taking into account specific uncertainties on not only material properties but also on environmental conditions, design models and the degree of validation. This document also provides provisions for semi-probabilistic design, including reliability-based calibration of partial safety factors and assessment of existing wind turbines. The probabilistic methods in this document are formulated generically and can be applied to structural and mechanical failure modes where a limit state equation can be formulated.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61400-1:2019, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-3-1, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC TS 61400-3-2, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

IEC 61400-6, *Wind energy generation systems – Part 6: Tower and foundation design requirements*

IEC 61400-13, *Wind turbines – Part 13: Measurement of mechanical loads*

IEC TS 61400-31, *Wind energy generation systems – Part 31: Siting risk assessment*

ISO 2394:2015, *General principles on reliability for structures*

EN 1990, *Eurocode – Basis of structural design*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given IEC 61400-1:2019 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1.1**limit state**

state of a structure beyond which the structure no longer satisfies the design criteria

3.1.2**design situations**

sets of physical conditions covering the conditions the structure will likely experience during a certain time interval for which the design will demonstrate that relevant limit states are not exceeded

Note 1 to entry: Internal force, moment, stress and strain are examples of action effect on structural members. Deflection and rotation are examples of action effect on the whole structure.

3.1.3**fatigue limit state**

structural failure due to damage accumulation under effects of repeated loading

3.1.4**ultimate limit states**

limit states which generally correspond to the maximum load bearing capacity

Note 1 to entry: This generally corresponds to the maximum load-carrying resistance of a structure or structural element but in some cases to a strain or deformation limit.

3.1.5**reliability**

ability of a structure or structural member to fulfil the specified requirements during the working life for which it has been designed

Note 1 to entry: Reliability is often expressed in terms of probability.

Note 2 to entry: Reliability covers safety, serviceability, and durability of a structure.

3.1.6**structural safety**

ability (of a structure or structural member) to avoid exceedance of ultimate limit states, including the effects of specified accidental phenomena, with a specified level of reliability, during a specified period of time

3.1.7**system reliability**

reliability of a system of more than one relevant structural member or a structural member which has more than one relevant failure mode

3.1.8**resistance**

ability of a structure (or a part of it) to withstand actions without failure

3.1.9**target reliability**

specified average acceptable failure probability that is to be reached as close as possible

Note 1 to entry: Reliability targets are generally model dependent and shall be set for each case considered based on the models used.

3.1.10**reliability-based design**

design procedure that is subjected to prescribed reliability level of the structure

3.1.11**robustness**

ability of a structure to withstand adverse and unforeseen events (like fire, explosion, impact) or consequences of human errors without being damaged to an extent disproportionate to the original cause

3.1.12**hazard**

unusual and severe threat, e.g. a possible abnormal action or environmental influence, insufficient strength or stiffness, or excessive detrimental deviation from intended dimensions

3.1.13**serviceability limit state**

limit state concerning the criteria governing the functionalities related to normal use

3.1.14**limit state function**

function $g(X_1, X_2, \dots, X_n)$ of the basic variables, which characterizes a limit state when $g(X_1, X_2, \dots, X_n) = 0$

3.1.15**basic variables**

variables representing physical quantities which characterize actions and environmental influences, material and soil properties, and geometrical quantities

3.1.16**model uncertainty**

basic variable related to the accuracy of physical or statistical models

3.1.17**probabilistic methods**

verification methods in which the relevant basic variables are treated as random variables, random processes, and random fields, discrete or continuous

3.1.18**reliability index**

β

real number quantifying the reliability of a structure

Note 1 to entry: $\beta = -\Phi^{-1}(P_f)$ where Φ^{-1} is the standard normal distribution and P_f is the annual probability of failure of the structure.

3.1.19**structural model**

idealization of the structure, physical, mathematical, or numerical, used for the purposes of analysis, design, and verification

3.1.20**first and second order reliability methods****FORM/SORM**

numerical methods used for determination of the reliability index β

3.1.21**reference period**

period of time used as a basis for assessing the design value of variable and/or accidental actions

3.1.22**load effect**

result of actions on a structural member (e.g. internal force, moment, stress, strain) or on the whole structure (e.g. deflection, rotation)

3.2 Symbols and abbreviated terms**3.2.1 Symbols**

A	parameter	-
B	parameter	-
c	environmental conditions	-
C	covariance matrix	-
d	distance between wind turbines	-
$D(t)$	accumulated damage at time t	-
D_{adm}	admissible fatigue damage	-
E	event	-
$E[]$	expected value	-
$F_X(x)$	probability distribution function for a stochastic variable X	-
$f_X(x)$	probability density function for a stochastic variable X	-
$f()$	function	-
$g(.)$	limit state equation	-
G	design equation	-
$h()$	function	-
H	Hessian matrix	-
H	hub height	-
k	shape parameter of the Weibull distribution function	-
K	material parameter of the SN-curve	-
L_k	characteristic value of load	-
$L(\theta)$	likelihood function	-
$LL(\theta)$	loglikelihood function	-
$L(X_L)$	extreme annual load effect	-
$LOAD$	load effect	-
$P_W()$	Weibull distribution	-
P_f	probability of failure	-
P_T	target probability	-
P_t	reference probability	-
$P_{f E}$	probability of failure conditional on event E	-
$P(\theta \varepsilon)$	probability of θ conditional on ε	-
$p_{c V}()$	probability of wind conditions c conditioned on mean wind speed V	-
$P_{f E,v,c}$	probability of failure conditional on an event E , mean wind speed v and specific wind conditions c	-

R_K	characteristic value of resistance	-
t_e	event duration	-
T_t	return period	-
X	stochastic variable	-
θ	statistical parameters in probability distribution functions $F_X(x \theta)$	-
Y	stochastic variable in hierarchical stochastic model	-
P_s	survival probability	-
L	load effect	-
$L_{\max}$	likelihood function	-
$LL_{\max}$	loglikelihood function	-
$L(X_L)$	extreme annual load effect	-
n	number of stochastic variables	-
R	resistance	-
R_0	model uncertainty	-
s	standard deviation	-
T	duration	s
T_L	design lifetime	y
T_t	reference period	y
T_n	stochastic variable Student t distributed with n degrees of freedom	-
V	wind speed	m/s
V_{cg}	extreme coherent gust magnitude over the whole rotor swept area	m/s
V_{gust}	largest gust magnitude with an expected return period of 50 years	m/s
V_{hub}	wind speed at hub height	m/s
W_X	random variable representing an environmental parameter X	-
$X_1, X_2, \dots$	stochastic variables	-
$x_1, x_2, \dots$	realisations of stochastic variables	-
X_{model}	model uncertainty	-
X_L	load stochastic variables	-
X_E	extreme load effect during event E	-
X_{Str}	model uncertainty stress calculation	-
Y'	test results	-
u_i^*	design point for stochastic variable no i	-
W	vector of stochastic variables representing different environmental parameters	-
z	design parameter	-
Z	standard normal distributed stochastic variable	-
α	wind shear power law exponent	-

β	reliability index	-
ε	data or evidence	-
δ	model uncertainty	-
$\Delta\sigma$	stress range	-
Δ	uncertainty on the Palmgren-Miner damage summation model	-
ΔP_f	annual probability of failure	-
γ_M	partial safety factor for resistances	-
γ_R	partial safety factor for resistances	-
γ_f	partial safety factor for loads	-
λ_F	annual failure rate	-
λ_E	rate of events	-
μ	mean value / expected value	-
ρ	air density	kg/m ³
ρ_{XY}	correlation coefficient between X and Y	-
θ	statistical parameter in distributions function	-
θ_{cg}	wind direction change magnitude	-
θ_e	extreme direction change magnitude	-
ν_i	rate of cycles at stress range	/y ⁻
σ_{eq}	equivalent stress range	-
σ_0	hub-height longitudinal wind velocity standard deviation	m/s
σ_1	hub-height longitudinal wind velocity standard deviation as a stochastic variable	m/s
σ_R	mean stress	MPa
Φ	standard normal probability distribution function	-
ϕ	standard normal density function	-
$\tau_{\ln R_0}$	precision	-

3.2.2 Abbreviated terms

COV	coefficient of variation
BEM	boundary element method
DEL	damage equivalent load
DLC	design load case
ECD	extreme coherent gust with direction change
EDC	extreme wind direction change
EOG	extreme operating gust
ETM	extreme turbulence model
EWM	extreme wind speed model
EWS	extreme wind shear

FEM	finite element method
FLS	fatigue limit state
FMEA	failure mode and effect analysis
FORM	first order reliability method
FRT	fault ride through
IFORM	inverse first-order reliability method
LVRT	low voltage ride through
MCMC	Markov Chain Monte Carlo
MTBF	mean time between failures
NTM	normal turbulence model
NWP	normal wind profile model
PSHA	probabilistic seismic hazard analyses
RBI	reliability- or risk-based Inspection planning
RNA	rotor nacelle assembly
S-N	stress-cycle curve for fatigue of materials
SORM	second order reliability method
ULS	ultimate limit state

4 Principal elements

4.1 General

The following subclauses specify essential requirements to the use of probabilistic design measures in order to ensure the structural and mechanical integrity of wind turbines. The specification of requirements applies to the design, siting and reassessment of a wind turbine system and its components, accounting for influences of the manufacturing, operations, maintenance, and environmental conditions.

This document provides appropriate methodologies, probabilistic models, and requirements for probabilistic assessment of components in line with IEC 61400-1. Probabilistic assessment is an alternative to the semi-probabilistic (deterministic) assessment procedures given in IEC 61400-1. The reliability assessment is performed for individual components and failure modes¹. The designer can select components and failure modes for probabilistic assessment, while the remaining failure modes shall be verified using traditional semi-probabilistic methods. It is allowed to do a full probabilistic analysis or use probabilistic methods to calibrate specific partial safety factors for use in semi-probabilistic assessment.

The main steps in a reliability assessment for a selected component and failure mode are the following:

- a) Determine appropriate component class and minimum annual reliability index (see 4.2).
- b) Model specification
 - i) Formulate limit state equations (see Clause 6).
 - ii) Develop appropriate probabilistic models for the variables in the limit state equations (see Clause 5 and additionally Clause 8 for siting).

¹ This document does not include requirements for the system reliability, thus the system reliability obtained through the requirements for individual components/failure modes is implicitly accepted.

c) Reliability analysis

- i) Perform a reliability analysis and compute the annual reliability index (see Clause 7).
- ii) Assess the accuracy of the computation and perform sensitivity studies (see Clause 7).

d) Assessment

- i) For design situations: Perform a design optimization loop oversteps b) and c) until a design is found where the minimum reliability is reached or exceeded in all years of the design lifetime.
- ii) For siting: The component has adequate reliability on a site if the minimum reliability is reached or exceeded in all years of the design lifetime.
- iii) For reassessment: The component has adequate reliability for continued operation for as many years as the minimum reliability is reached or exceeded.

4.2 Minimum reliability level and component classes

For ultimate limit states², each component shall meet or exceed the minimum reliability levels specified in Table 1 for its respective component class (consequence of failure). If human health and/or environment is at risk, a site-specific risk assessment according to IEC TS 61400-31 (or equivalent) should be performed. The minimum reliability level can be achieved through a combination of design, prescribed scheduled maintenance and parts replacement, and health monitoring. Minimum reliabilities for special safety class wind turbines (as defined in IEC 61400-1:2019, 5.3) should be agreed between the manufacturer, customer and relevant authorities. Minimum reliability levels for serviceability limit states should be defined based on their consequences, see ISO 2394 and (JCSS PMC 2001).

Table 1 – Minimum reliability requirements³

Component class	Maximum allowable annual probability of failure	Minimum annual reliability index
Component class 1	10^{-3}	3,1
Component class 2	5×10^{-4}	3,3
Component class 3	10^{-4}	3,7
For both fatigue and ultimate limit state, the minimum is given for the year with the largest annual failure probability (for fatigue conditional on surviving until given year)		

4.3 Limit states

For the failure modes selected for probabilistic assessment, limit state equations shall be formulated based on the deterministic design equation, representing variables by their probability distributions, instead of using characteristic values and partial safety factors. Uncertainties related to external conditions, load assessment, and resistance (as described further in Clause 5) should be included either directly (e.g. the input variable is represented directly as a random variable in the limit state equation) or indirectly (e.g. the effect of uncertainty on one or more variables is represented as a model uncertainty multiplied on the load effect) in the limit state equation.

² Ultimate limit states include ultimate strength analysis, fatigue failure, stability, and critical deflection analysis as defined in IEC 61400-1:2019, 7.6.

³ The reliability requirements correspond to the target values given in ISO 2394 for 'Large relative cost of safety measure' for Consequence Classes 2, 3, and 4.

Reliability assessments can be performed for ultimate and serviceability limit states such as:

- exceedance of the ultimate strength;
- fatigue failure;
- static instability;
- dynamic instability;
- component interference due to deformation;
- extreme vibrations;
- loss of control functionality;
- permanent deformations.

4.4 Data validity

Probabilistic models for physical quantities shall be based on representative data, and model uncertainties should be assessed through a combination of tests and measurements such as:

- material tests;
- test of sub-components/scaled components;
- full-scale component tests;
- load measurement campaigns (e.g. prototype testing);
- environmental data (e.g. met-mast data);
- operational data.

The availability of data depends on whether the reliability assessment is made in relation to design, siting, or reassessment. Examples of typical situations and available data are:

- design of RNA components for an IEC class or class S turbine (tests on material and sub-components, data from other wind turbine models);
- site-specific design of tower, sub-structure and/or foundations, or site assessment of an IEC class or class S turbine for a specific site (tests on material and components, load measurement campaigns, environmental data);
- re-assessment of a wind turbine during or near the end of the operational phase (tests on material and components, load measurement campaigns, environmental data, operational data, condition monitoring data).

The influence of the following sources of uncertainty should be included in the analysis where relevant:

- deviation in raw material quality;
- nonconformity of finished parts to quality control specifications;
- unknown part defects outside the scope of quality control specifications;
- nonconformity of installation procedures to specifications;
- site environmental conditions;
- variability in operational practices, including controller issues;
- variability in maintenance practices;
- nonconformity of component repairs and replacement with specifications or standard industry practice.

5 Uncertainty representation and modelling

5.1 General

5.1.1 Uncertainties

The uncertainties associated with the external conditions, load assessment, structural resistance and electrical/mechanical component reliability related to wind turbine control or safety system should be modelled for the wind turbine lifetime as part of a reliability analysis. The following text is based on ISO 2394.

5.1.2 Types of uncertainty

Various sources of uncertainty as for example natural/physical variability, statistical uncertainties, measurement uncertainties and model uncertainties exist. Natural/physical uncertainties are often referred to as aleatory uncertainties which cannot be reduced. Statistical, measurement and model uncertainties are often referred to as epistemic uncertainties which can be reduced e.g. through additional measurements.

The natural/physical uncertainties are typically uncertainties related to the external conditions, the geometry of the structure and the material properties.

The statistical uncertainties originate from limited information and data about external conditions, material properties, load validation, number of simulations, etc.

The measurement uncertainties originate from uncertainty in measurement setup, equipment, calibration or analysis of tests. The list of contributions to measurements uncertainty should be complete for the application and reflect the information available about accuracy.

The model uncertainties originate from idealisations and imperfections associated with describing a physical phenomenon using mathematical models. This includes the formulation of the models (M), that attempt to represent the real world (Y) based on a given input (X), as well as the statistical parameters (θ) of the model that are subject to uncertainty, see Figure 1. Model uncertainty is e.g. associated with aeroelastic models, finite element models, reduced-order representations and failure criterions.

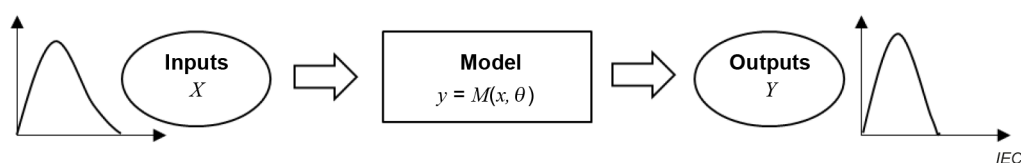


Figure 1 – Application of a mathematical model to estimate an output based on a given input

5.1.3 Interpretation of probability and treatment of uncertainty

In structural reliability analysis, the Bayesian interpretation of probability in ISO 2394 should be considered as the most adequate basis for the consistent representation of uncertainties, independent of their sources. It facilitates the joint consideration of analytically assessed uncertainties, evidence as obtained through observations and subjectively assessed uncertainties (expert knowledge), see Annex A.

Subjective information can for instance be used to quantify the expected variation for a very limited test sample based on previous test samples or to quantify physical or model uncertainties which either cannot or are not practically possible to measure. However, subjectively assessed uncertainties should be used with caution and the information used should be documented and preferably obtained through a structured process.

In Bayesian probability theory, the values for probabilities are estimated based on an adequate combination of data, theoretical arguments, and judgment. There is no distinction in the treatment between aleatory and epistemic uncertainty.

Considering the probabilistic modelling of a random basic variable X , the principle in Bayesian probability analysis is to model one or more of the statistical parameters θ (e.g. the mean and standard deviation) of the probabilistic model (e.g. the probability distribution function) as random variables themselves.

All uncertainties that are of importance for the reliability analysis of a wind turbine or parts thereof shall be included in the analysis using the theory of probability. A systematic approach based on a hierarchy modelling of uncertainties can support the identification of contributions to uncertainty.

5.1.4 Probabilistic model

Depending on the nature of the reliability problem, basic variables can be represented as random variables, random processes and random fields, discrete as well as continuous.

The probabilistic models should describe the uncertainties of individual random basic variables, but also accommodate the consideration of the dependencies among them.

The uncertainty in the basic variables and the dependencies among them can normally be modelled by probability distribution functions $f_X(x)$ and correlation coefficients ρ focussing on the application of interest (e.g. extreme values).

A dependent or hierarchical modelling of uncertainties is recommended, where applicable. The dependent or hierarchical model assumes that a random quantity Y can be written as a function of several variables, each one representing a specific type of variability:

$$Y_{ijk} = f(X_i, X_{ij}, X_{ijk}) \quad (1)$$

where the variables X_i , X_{ij} , X_{ijk} represent various origins, time scales of fluctuation, or spatial scales of fluctuation.

This modelling approach is for example relevant for the wind conditions, where the wind speed standard deviation σ_1 (turbulence) is dependent on e.g. the 10 min mean wind speed V_{hub} and terrain roughness.

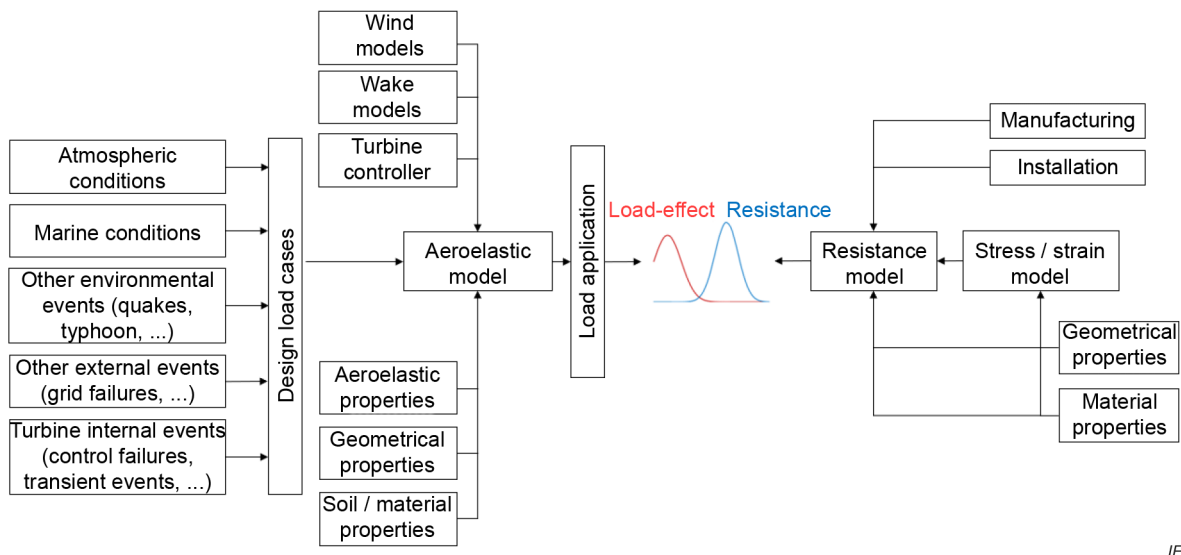
The probabilistic models should when relevant also accommodate the updating of the models by additional information, which can become available with, for example, experiments, tests, inspections, and monitoring. The Bayesian updating formula provides the operational basis for this.

The description of uncertain quantities by probabilistic models should correspond to well-defined outcome spaces (or populations) and the results of the probabilistic analysis are only valid for the same sets.

The probabilistic models can be determined based on information from different e.g. wind turbine types, design concepts or site conditions. In these cases, it should be justified that the probabilistic model is representative and potential residual uncertainty should be covered by model uncertainty.

5.1.5 Uncertainties for wind turbines

Accounting for uncertainties in probabilistic design can be done in many ways. A typical flow chart and uncertainties which could be considered in probabilistic design for wind turbines is shown in Figure 2 and the principles for assessment of the individual uncertainties are described in the following subclauses.



IEC

Figure 2 – Typical flow chart and uncertainties to be considered in probabilistic design of wind turbine components

The design load cases defined in IEC 61400-1, IEC 61400-3-1 and IEC TS 61400-3-2 specify the minimum number of design situations which should be considered. The uncertain input to the design load cases is listed in the following:

- Atmospheric conditions represent the uncertainty in e.g. mean wind speed, extreme wind speed (including tropical cyclones), turbulence, wind shear, air density and gust events.
- Marine conditions represent the uncertainty in e.g. wave conditions, current, tides and storm surge.
- Other environmental events represent the uncertainty in e.g. temperature, lightning, ice conditions and earthquakes.
- Other external events represent the uncertainty in e.g. grid fault, loss of electrical network, low voltage ride through.
- Turbine internal events represent the uncertainty in e.g. controller failures (primary and secondary layer protection functions), overspeed, actuators and braking systems.

The aeroelastic model is normally relying on a number of sub-models:

- Aerodynamic models represent the uncertainty in e.g. the blade element momentum model, or dynamic stall model.
- Structural models represent the uncertainty in e.g. the blade beam model.
- Mechanical models represent the uncertainty in e.g. the pitch system model and the gearbox model.
- Electrical models represent the uncertainty in e.g. the generator or the converter model.
- Wind models represent the uncertainty in e.g. the Mann or Kaimal turbulence models.
- Wake models represent the uncertainty in e.g. the added wake turbulence method or dynamic wake meandering model.
- Turbine controller represents the uncertainty in e.g. a simplified controller implementation.

Additionally, the aeroelastic model is based on some input parameters which normally are constant for the various design load cases:

- Aerodynamic properties represent the uncertainty in e.g. lift and drag coefficients.
- Geometrical properties represent the uncertainty in e.g. thickness and length.
- Soil/material properties represent the uncertainty in e.g. stiffness.

The aero-elastic simulations are normally post-processed in order to determine the input to the resistance model:

- Load application represents the uncertainty in e.g. extrapolation, contemporaneous loads, rainflow cycle counting and Miner's rule.

The resistance model or failure criterion is based on the following input parameters:

- Manufacturing represents the uncertainty in e.g. the manufacturing quality.
- Installation represents the uncertainty in e.g. the installation process and quality.
- Geometrical properties represent the uncertainty in e.g. thickness and length.
- Material properties represent the uncertainty in e.g. stiffness and strength.
- For some materials, such as composites or concrete, additional uncertainties shall be considered due to temperature, degradation, ageing, brittleness or other relevant effects.

Additionally, the resistance model is often dependent on a stress/strain model:

- Stress/strain model represent the uncertainty in stress and strain assessment for a load application, e.g. through a finite-element model.

The individual physical, model, measurement and statistical uncertainties can be quantified directly and propagated through the flow chart in order to determine the resulting uncertainty in the load effect or resistance.

5.2 External condition uncertainty modelling

5.2.1 General

The external conditions refer to the environmental and electrical conditions which affect the wind turbine or parts thereof. Environmental conditions can in general be separated into wind, marine, soil and other conditions.

The individual environmental conditions should be modelled by stochastic models established based on the standard conditions used for IEC class verification as defined in IEC 61400-1, IEC 61400-3-1 and IEC TS 61400-3-2 or representative measurements for the quantity and application of interest. The term "representative" should be considered in relationship to the measurements available and expert knowledge used for defining the standard conditions used for IEC class verification.

The design load cases in IEC 61400-1, IEC 61400-3-1 and IEC TS 61400-3-2 define the relevant design situations for a wind turbine for which stochastic models can be established.

5.2.2 Wind conditions

The atmospheric conditions can in general be separated into the standard wind conditions and other conditions defined in IEC 61400-1. The standard wind conditions are generally established by determining a characteristic value (typically 50-year value) for a single wind parameter or wind event e.g. turbulence or gust. The potential interaction of the individual wind conditions and non-linear interaction of the wind turbine controller can influence the wind turbine response and should be considered when the stochastic models are established.

Probabilistic models established for IEC class type certification (I-III & A+-C) should be based on IEC 61400-1 when available. Other wind conditions can be modelled by probabilistic models when these are in alignment with the general design philosophy in IEC 61400-1. As an example, the air density can be modelled by a probabilistic model with a mean value equal to $1,225 \text{ kg/m}^3$ as specified in IEC 61400-1 and other parameters determined based on measurements. Probabilistic models established for IEC class "S" should be specified by the designer.

The probabilistic models can be developed by identifying the standard wind conditions (e.g. gusts or wind direction changes) from IEC 61400-1 or from wind or turbine measurements. The probabilistic models shall represent the measurement and statistical uncertainties in the measurements in addition to the physical uncertainties of the wind conditions.

The turbulence model describes the spatial and time variation in the wind velocity field established through longitudinal, lateral and upward vector components, generally consistent with a specified 10-min average wind speed at hub height and reference turbulence intensity, see IEC 61400-1:2019, Annex C. The model and statistical uncertainty related to the turbulence model should be quantified e.g. as part of the load uncertainty modelling, see 5.3.

5.2.3 Normal wind conditions

5.2.3.1 General

The normal wind conditions are represented by the mean wind speed distribution, the normal wind profile (NWP) and the normal turbulence model (NTM) in IEC 61400-1.

The mean wind speed distribution $P_R(V_{\text{hub}})$ for the wind speed at hub height V_{hub} (10 min reference period) is according to IEC 61400-1 defined as a Rayleigh distribution for the different IEC classes. The Rayleigh distribution is a special case of the more general Weibull distribution which normally is used to characterise the mean wind speed distribution in probabilistic models. The NWP represent a deterministic wind profile (no turbulence) modelling the variation of mean wind speed over the rotor using average conditions for wind shear and air density. The NWP is used in combination with specific controller actions like start-up or shutdown and serves as the basis upon which other wind events are added. Uncertainty modelling for the NWP is therefore normally not relevant or replaced by other specific wind conditions as e.g. the NTM model.

The NTM represent normal stochastic wind (turbulence) conditions using a distribution for the turbulence and average conditions for wind shear and air density to model normal operating conditions. The stochastic representation of the NTM should according to IEC 61400-1 be based on a Weibull distribution $P_W(\sigma_1 < \sigma_0)$ for the wind speed standard deviation σ_1 (10 min reference period) for IEC class verification. The uncertainty modelling for the NTM should cover the natural variation of mean wind speed and turbulence. Additionally, the uncertainty modelling can cover variations in wind shear, air density and wind direction along with the potential dependence/correlation between these due to different atmospheric stability conditions.

5.2.3.2 Extreme wind conditions

The extreme wind conditions are in IEC 61400-1 represented by the extreme wind model (EWM), extreme operation gust (EOG), extreme turbulence model (ETM), extreme direction change (EDC), extreme coherent gust with direction change (ECD) and extreme wind shear (EWS). These events are defined to cover all relevant extreme wind conditions for a wind turbine and are defined by extrapolation of a single wind parameter or wind event (Stork, 1998). The events should therefore in general not be combined with variations in other wind conditions.

The stochastic models for the extreme wind conditions should correspond to an annual reference period when combined with specific operational states e.g. grid-loss, start-up or shutdown. This ensures consistency with the target reliability level specified in Clause 4.

The EWM represents conditions with extreme wind speeds. The EWM is in IEC 61400-1 defined by the maximum 10 min mean wind speed with a return period of 1 year and 50 years, which represent the characteristic value. The uncertainty modelling for the EWM represents the physical uncertainty in the annual maximum wind speed, including inter-annual variability and measurement uncertainties.

The EOG represents the extreme gust which occurs together with a specific operation event such as a start-up or shutdown to give a combined return period of 50 years. The EOG can according to IEC 61400-1 be replaced with the NTM model for DLC 2.3 and by the ETM model for DLC 3.2 and 4.2 offering an easier combination with specific operational states.

The EOG is in IEC 61400-1 defined by a gust profile expressed in space over the event duration and described by the gust magnitude V_{gust} and duration T . The uncertainty modelling for the EOG should represent the uncertainty in the maximum gust magnitude and duration. The gust profile can be considered deterministic.

The ETM represents the 50 year extreme turbulence conditions at a given mean wind speed V_{hub} , based on the inverse first order reliability method (IFORM) using the models for the normal wind conditions in 5.2.3, see Annex B. Measurement uncertainty of the turbulence intensity shall be considered additionally. Alternatively, the uncertainty model for the ETM can be represented by the conditional distribution for the annual extreme turbulence at a given mean wind speed.

The EDC represents the extreme direction change which occurs together with a specific operation event such as a start-up with a return period of 50 years. The EDC is in IEC 61400-1 defined by a wind direction variation, expressed over the event duration, which is described by the extreme direction change magnitude θ_e and duration T . The uncertainty modelling for the EDC should represent the uncertainty in the extreme wind direction change. The wind direction profile can be considered deterministic.

The ECD represents the 50-year extreme coherent gust with direction change occurring during normal operating conditions. The ECD is in IEC 61400-1 defined by a gust and wind direction variation, expressed over the event duration, which is described by the coherent gust magnitude V_{cg} , wind direction change magnitude θ_{cg} and duration T . The uncertainty modelling for the ECD should represent the uncertainty in the extreme coherent gust and wind direction change. The gust and wind direction profile can be considered deterministic.

The EWS represents the 50-year extreme transient events with horizontal and vertical wind shear. The EWS is in IEC 61400-1 defined by a wind speed profile for the event duration, which is described by the wind shear magnitude parameter and duration T . The uncertainty modelling for the EWS should represent the uncertainty in the extreme horizontal and vertical wind shear magnitude. The wind speed profile can be considered deterministic.

5.2.4 Other conditions

5.2.4.1 General

Other atmospheric conditions include e.g. wake conditions, tropical cyclones, ice formation and extreme temperatures are listed in IEC 61400-1 and IEC 61400-3-1.

Wake conditions can be modelled according to IEC 61400-1:2019, Annex E. The model uncertainty related to the wake modelling should represent the fidelity and validation of the model, see 5.3. Additionally, the physical and statistical uncertainty in the wake conditions and the frequency of their occurrence should be considered.

Tropical cyclone conditions can be represented by the extreme wind model (EWM), but the coefficient of variation (COV) for the annual extreme wind speed/pressure is normally higher than for other extreme wind conditions and should therefore be representative for these events.

Ice formation can be modelled according to IEC 61400-1:2019, Annex L. The physical and model uncertainty in the accretion of ice or snow on the structure should be considered along with the frequency of occurrence.

The additional environmental conditions listed in IEC 61400-1 and IEC 61400-3-1 (with the exception of earthquakes and tsunamis) can in most probabilistic analysis be represented by a deterministic value corresponding to the expected value or a low/high quantile. In case the additional environmental conditions have a significant impact on the probabilistic analysis, stochastic models should be established.

5.2.4.2 Earthquakes

Earthquakes generate loads in terms of ground acceleration acting at the foundation of a wind turbine, which is specified by a spectrum at a given return period. IEC 61400-1 specifies the load level for design with a return period of 475 years and defines superposition with other loads and associated safety factors. The widely used return period of 475 years corresponds to a 10 % probability of exceedance in 50 years.

Seismic loading is highly dependent on local conditions and is defined in seismic codes, which often demand, besides prescription of the load spectrum, the use of certain models for assessment of structural earthquake resistance.

Typically, probabilistic seismic hazard analyses (PSHA) are carried out in order to define relevant seismic loading for a specific wind turbine site. By use of PSHA, the probability of exceedance of a specified level of ground motion can be calculated.

5.2.5 Electrical network conditions

The external electrical conditions at the wind turbine terminals influence the reliability of both electrical and mechanical components dependent on the design of the energy conversion system.

IEC 61400-1 provides guidance on the types of electrical network conditions. Statistics on such conditions are not commonly available and vary from country to country. National grid utilities provide some information publicly or on demand. Furthermore, measurements at wind turbine sites can provide data for defining appropriate discrete or continuous distributions.

An example for application of continuous distribution is the range of grid voltage and frequency as an occurrence probability distribution.

Discrete distributions are more suited for less frequent conditions, such as, for example, power ramps, temporary derating, grid loss and fault ride through (FRT) events.

The latter two, grid loss and FRT, are part of the standard load case definitions in IEC 61400-1. While grid loss is fully defined by its occurrence rate, FRT events have a number of other attributes that shall be considered such as magnitude and length of the voltage drop or peak, level of symmetry and number of consecutive events. These attributes can have a significant load effect on both, the mechanical and the electrical system. Modelling these attributes requires appropriate information on the occurrence distribution as well as on suitable binning of the event types.

5.3 Load uncertainty modelling

5.3.1 General

The load uncertainty modelling refers to the uncertainties in the assessment of the load effect on the individual wind turbine components and subcomponents. As part of the probabilistic modelling, uncertainties in all steps of the load assessment procedure shall be considered and included, see also Figure 2:

- a) Input to the aeroelastic model (such as external conditions, structural design, aerodynamics and wind turbine controller) is defined.
- b) The direct outcome of the aeroelastic simulations are time series of section forces in components (modelled as finite elements in the aeroelastic simulations), for combinations of the input variables.
- c) Relevant load effects are extracted from the time series for each considered load case using appropriate methods (e.g. extreme values, rainflow cycle counting and Markov matrix).
- d) Extracted load effects are combined with their probability of occurrence to obtain the long-term distributions.
- e) Load effects in critical locations of components are estimated using transfer functions based on FEM or analytical/empirical formulations.

The assessment of uncertainties should be performed in relation to relevant limit state equations for selected components, failure modes and design load cases.

5.3.2 Aeroelastic model

Uncertainty on the input to the aeroelastic model (see Figure 3) cause uncertainties on the output. Therefore, uncertainties related to the input should be quantified on the base level and propagated through the computational models used in the load assessment. This includes uncertainties in the assessment of section forces using an aeroelastic model and if relevant assessment of load effects based on section forces using FEM models or analytical models. The formulation of the uncertainty model should consider the influence of nonlinearities in the relation between section forces and load effects.

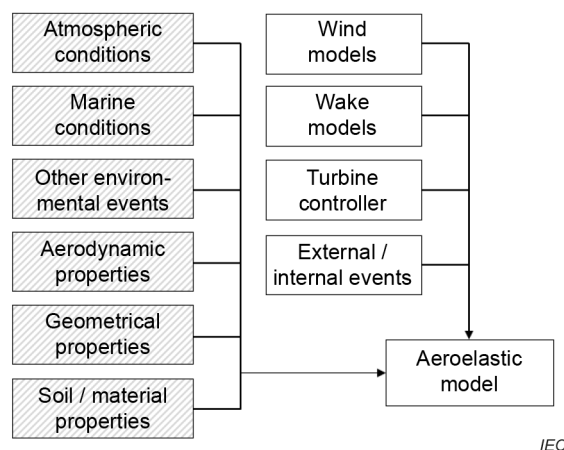
The uncertainty propagation can be performed by simulation-based methods (Monte-Carlo, importance sampling) or local expansion methods (Taylor series) to determine the resulting model uncertainty for the considered component, failure mode and design load case. The uncertainty propagation should take any potential correlation between uncertainties in the input parameters into account. The convergence of the uncertainty propagation should be assessed. The uncertainty propagation can be performed with simplified simulations models like e.g. surrogate models.

For some input to the aeroelastic model, it is not possible to propagate the uncertainties (e.g. model choices) through the aeroelastic model. The uncertainty in these inputs should therefore be quantified based on measurements, model variations or subjective information and represented by model uncertainties, see Formula (2), Figure 1 and Annex A.

$$Y = \delta \times M(X, \theta) \quad (2)$$

where δ is a stochastic variable representing the model uncertainty.

A typical split between the uncertainties which should be propagated through the aeroelastic model (shaded) and those which should be represented by model uncertainty is shown in Figure 3.



See also the typical flow chart in Figure 2.

Figure 3 – Typical split between uncertainties which should be propagated through the aeroelastic model (shaded) and those which should be represented by model uncertainty

Other contributors to the aeroelastic model uncertainty are uncertainties related to the methods used for wind turbine modelling and simulation (e.g. BEM theory, multibody, FEM), the discretization in finite elements (degrees of freedom) and time domain (simulation time steps).

The model uncertainty related to the aeroelastic model will in general be dependent on the fidelity and validation of the model applied. The model uncertainty can be determined based on load measurements and validation campaigns from e.g. proto-type turbines according to IEC 61400-13, where measurement load cases corresponding to the design load cases are defined.

The model uncertainty for the aeroelastic model with respect to extreme loads can be determined based on 10-min statistics (min, max, mean, std) from the measurement load cases defined in IEC 61400-13. The model uncertainty with respect to fatigue loads can be determined based on 10-min damage equivalent loads (DEL). The model uncertainty can be determined based on Clause A.4, but measurement uncertainty will typically be included in the assessment, potentially together with other model uncertainties listed in Figure 2 and Figure 3.

The assessment of the model uncertainty should focus on the considered design situation, components, and environmental conditions of interest. Statistical uncertainty due to the limited amount of measurement/validation data available should be considered if the data requirements in IEC 61400-13 are not fulfilled.

If the uncertainty propagation or assessment of model uncertainties have been performed for a specific component, failure mode or design load case, the resulting model uncertainty can be re-used for similar wind turbine types and design situations when appropriately justified.

5.3.3 Extreme loads

The estimated extreme loads are dependent on the number of simulations and consideration should be given to the convergence criteria and the statistical uncertainty related to the assessment. The extreme loads are normally assessed using one of the following methods:

- Extrapolation methods typically involving peak extraction or inverse first-order reliability methods (IFORM). The independence of the peaks and goodness of fit for the distribution function used to determine the exceedance probability of e.g. 50 years should be evaluated.
- Averaging methods where the extreme load is determined using a specific averaging scheme (e.g. mean value of the largest half) of the peak values from each time series. The statistical uncertainty related to the number of simulations should be evaluated.

- Prototype/field measurements where the uncertainty related to the aeroelastic model is omitted, but measurement uncertainties are introduced. The statistical uncertainty related to the number of measurements should be evaluated.

5.3.4 Fatigue loads

Fatigue damage occurs from an accumulation of cycles due to the fluctuating loads. The fatigue loads are for structural components normally represented by the number of load cycles with different ranges and mean load levels extracted by e.g. the rainflow cycle counting method, whereas the fatigue loads for mechanical components normally are represented by the time different load levels occur represented by duration loads.

The model and statistical uncertainty related to the fatigue load estimation should be evaluated. The model uncertainty related to the fatigue load estimation (e.g. rainflow cycle counting) is normally assessed together with the model uncertainty for the fatigue damage estimation (e.g. Miner's rule).

5.4 Structural resistance uncertainty modelling

5.4.1 General

The uncertainty in structural resistance is in general dependent on the variation in geometrical and material properties, resistance models along with the manufacturing methods and quality.

The structural resistance shall according to IEC 61400-1 be analysed for the following limit states where relevant:

- analysis of ultimate strength;
- analysis of fatigue failure;
- stability analysis;
- critical deflection analysis.

Each type of analysis requires a different formulation of the limit state function and deals with different sources of uncertainties, see 5.1.2. The limit state function can in general be formulated based on the design requirements for the individual component specified in e.g. IEC 61400-1, IEC 61400-6 or IEC 61400-8.

Further guidance on the assessment of uncertainties, characteristic values and partial safety factors for structural resistance is given in IEC 61400-1:2019, Annex K.

5.4.2 Geometrical properties

The uncertainty in geometrical properties can either be estimated based on observations/measurements or the manufacturing tolerance specification defined for the considered component along with the applied quality control.

The uncertainty in geometrical properties is for most wind turbine components small and has therefore normally minor effect on the structural resistance. If this is justified the geometrical properties can be modelled deterministic in the limit state function.

5.4.3 Material properties

The uncertainty and potential bias in the material properties can either be estimated based on measurements or the manufacturing/supplier specifications for the considered material along with the applied quality control.

The uncertainty modelling for the material properties and the associated structural resistance should consider the failure mode (brittle vs. ductile), scale effects and degradation during the design lifetime.