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Probabilistic methods for wind turbine blades

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EUROPEAN ENERGY RESEARCH ALLIANCE

<u>**SUB-PROGRAMME on Structural Design & Materials**</u>

A sub-programme within the:
Joint Research Programme on Wind Energy

REPORT RT2
Probabilistic methods for wind turbine blades

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1. Introduction

The European Energy Research Alliance (EERA) has as a key purpose to elevate cooperation between national research institutes to a new level, from ad-hoc participation in joint projects to collectively planning and implementing joint strategic research programmes.

The RES directive and the SET Plan enforce a high rate of deployment of wind energy, on- and offshore for the European Union's member states leading to a high challenge for research in the two priority areas: Integration and Offshore. Wind energy was therefore at an early stage identified as an area for a joint research programme where the key players are the national wind energy research institutes but open to and encouraging universities to participate in the activities.

A key objective of the joint programme is to address the research challenges of the European Industrial Initiative on Wind Energy in the "Wind Energy Roadmap".
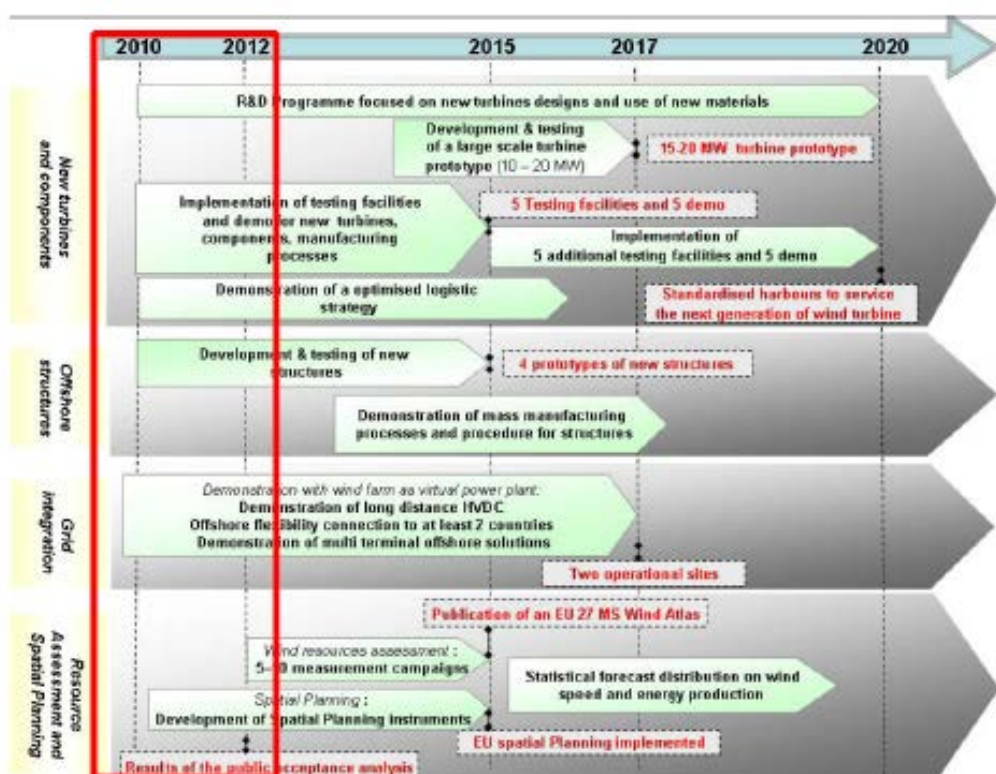
Source: European Commission, "A Technology Roadmap" - SEC(2009) 1295

Figure 1.1. European Wind Energy Technology Roadmap 2010-2020

The road map comprises activities during 2010-2020 on
1. New turbines and components
2. Offshore technology
3. Grid integration
4. Resource assessment and spatial planning

The EERA Joint Programme on Wind Energy aims at accelerating the realization of the SET-plan goals and to provide added value through:

✓ Strategic leadership of the underpinning research

- ✓ Joint prioritisation of research tasks and infrastructure
- ✓ Alignment of European and national research efforts
- ✓ Coordination with industry, and
- ✓ Sharing of knowledge and research infrastructure.

The EERA JP Wind is characterized by the four distinct dimensions which are general for solving scientific problems:

1) Theory and models,
2) Data acquired from well focused experiments
3) Verification of theory and models by the data
4) Development of new generic technology concepts

In practical terms, the participants have agreed on organizing themselves with shared model developments, shared databases and commonly developed schemes for verification as well as sharing research facilities. The joint programme comprised five strategically important research sub-programmes:

- Wind Conditions
- Aerodynamics
- Structures and Materials
- Grid Integration and Offshore Wind Energy
- An infrastructure sub-programme: Research Facilities

The overall objective of the sub-programme on Structures and Materials [1.1] is to reduce the uncertainty in the design of structural load carrying components as well as machinery components in order to increase cost efficiency and reliability and allow for optimization, innovations and upscaling of future wind turbines. The research is structured around development of theory and models, data from experiments and validation.

Five long term Research Themes (RTs) are addressed:

RT1:   Efficient blade structures
RT2:   Structural reliability methods
RT3:   New material models and life prediction methods
RT4:   Design process of wind turbine components
RT5:   New concepts and features, material state monitoring and repair solutions for blades

RT2 will focus on the development and validation of models for probabilistic assessment and reliability estimation of wind turbine structural components. Activities focusing on major components of the wind turbine within this RT are the following:

- Development/improvement & validation of stochastic methodologies for the reliability assessment of strength and stability of wind turbine blades

- Development of stochastic models and probabilistic methods for the reliability assessment of substructures (mooring lines, anchoring systems, umbilical cables)

- Development of probabilistic assessment methods of selected structural components (tower, main frame, hub, etc.)

Specific actions to serve the needs of this long term RT again include collection of available models and required input, development and/or improvement of models where necessary, assessment and validation of models. The developed methods are envisaged to provide part of the required input for the development of maintenance strategies, in combination with relevant models of RT1.
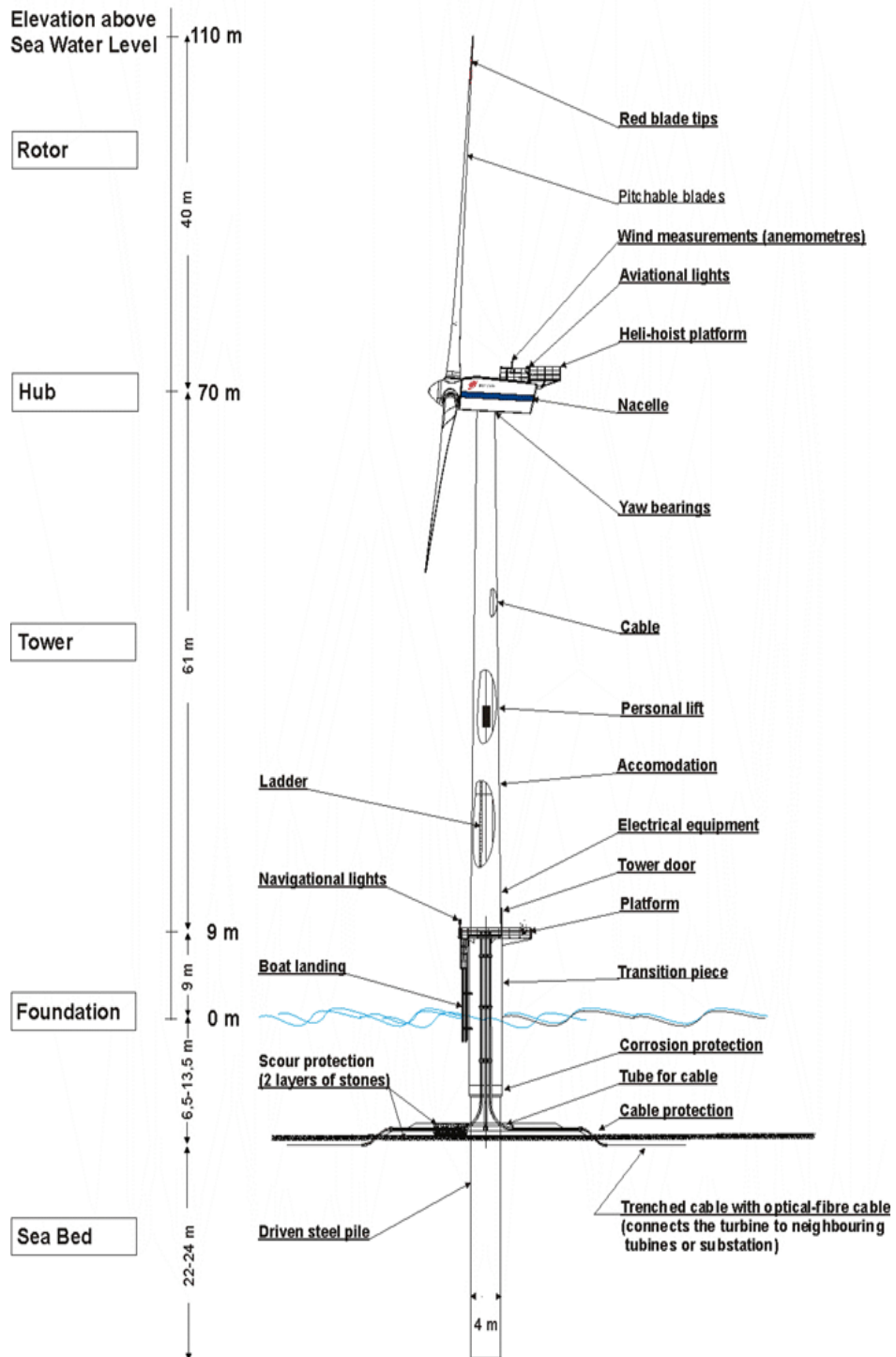
Figure 1.2. Principal components and dimensions of an offshore monopile wind turbine structure [1.2].

2. Objective

The main objective for this report is to describe the methods currently available for probabilistic modelling of wind turbine blades and define future research needs.

3. Wind turbine blade technology

The design of the wind turbine blade is a compromise between aerodynamic and structural considerations. Aerodynamic considerations usually dominate the design for the outer two thirds of the blade, while structural considerations are more important for the design of the inner one third of the blade [3.1]. Traditionally this is an iterative process where the structural design group and aeroelastic design group work on the blade design alternately. However, research trends go towards a more integrated approach.

Blade construction and manufacturing

Wind turbine blades are advanced structural constructions making use of composite laminates, sandwich core materials, coating and adhesive joints. Differences in manufacturing processes, material selection and design philosophy influence the design. However, most blade designs are structurally similar and can basically be considered as a load-carrying beam (spar) enclosed by a shell.
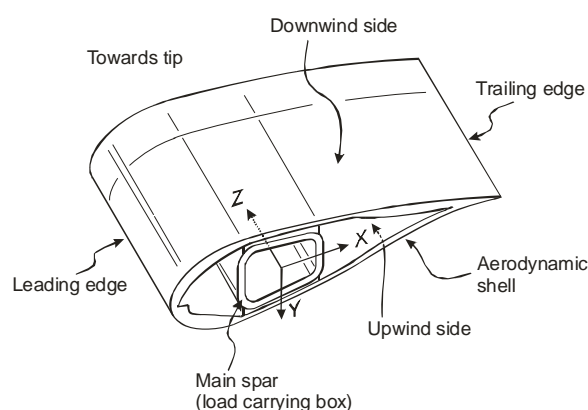

Figure 3.1. Wind turbine blade cross-section [3.2].

The load-carrying flange of the load-carrying beam is usually a thick monolithic laminate with 80-90% of the fibres in the longitudinal direction. The load-carrying flange is either integrated in the aerodynamic shell or part of a box girder which is glued to the inside of the aerodynamic shell. In both cases the load-carrying flange is supported by one or more shear webs.

The manufacturing of wind turbine blades is primarily done using pre-pregs or vacuum assisted resin transfer moulding. Often different segments of the blade are manufactured separately and then joined together using adhesives.

Materials

Materials used for wind turbine blades are primarily composite materials which for wind turbine blades are long aligned fibres embedded in a continuous material called the matrix material. E-glass is most commonly used as fibres, but more expensive carbon fibres are also being used increasingly, in order to increase blade stiffness and save weight. The matrix material is also an important concern for wind turbine blades. Currently, polyester is the most common choice as the matrix for glass fibre laminates, but epoxy resins and vinylester are also used because of their superior mechanical properties.

Sandwich panels are widely used in the aerodynamic shell of the blade and for the shear webs in most spar designs. The core material is low-density materials, primarily balsa wood or polymer foams. The skins are primarily thin composite laminates with fibre in at least two different directions.

Since most wind turbine blades are bonded together, the adhesives used to join the different blade segments have a direct influence on the reliability of the blade. The adhesives utilized in blades are primarily epoxy, polyurethane and methacrylate based adhesives.

The surface of wind turbine blades are painted with gelcoats to protect the composite materials from damage originating from UV-radiation and to limit the environmental exposure to the blade, e.g. humidity which may decline the mechanical properties of the composite materials [3.3].

Design methods

Wind turbine blades are designed using different numerical tools. The simplest ones are 2D sectional analysis tools based on the standard formulation of Euler-Bernouilli or Timoshenko Beam's Theory. More advanced beam tools are based on the variational asymptotic method and determination of cross section stiffness properties using a finite element based approach. Such as Variational Asymptotical Beam Section Analysis (VABS) by Hodges [3.4] and Beam Cross Section Analysis Software (BECAS) by Blasques et al [3.5, 3.6]. With these methods, a beam with arbitrary cross sections consisting of different materials can be analysed by a one-dimensional beam theory. The method provides a simple way to characterize strain in an initial curved and twisted beam and all components of cross-sectional strain and stress can be accurately recovered from the one-dimensional beam analysis. The global deflection of wind turbine blades, Eigen frequencies and other global behaviour can in general be analysed with good accuracy by use of beam models. However, if greater accuracy is needed or more locally structural phenomena need to be analysed, more detailed shell and/or solid FE models must be used.

Anyway experimental testing of materials, structural details and the full blade also plays an important role.

Blade testing

Full scale testing is mandatory for certification of large wind turbine blades. The basic purpose of these blade tests is to demonstrate that the blade type has the prescribed reliability with reference to specific limit states with a reasonable level of certainty. According to Det Norske Veritas (DNV) [3.7], a limit state is defined as a state beyond which the structure no longer satisfies the requirements. The following categories of limit states are of relevance for wind turbine blades: ultimate limit state (ULS), fatigue limit state (FLS), and serviceability limit state (SLS). The blade should be manufactured according to a certain set of specifications in order to ensure that the test blade is representative of the whole series of blades. In other words, the purpose of the blade tests is to verify that the specified limit states are not reached and that the type of blade possesses the projected strength and lifetime.

Normally, the full-scale tests used for certification are performed on a very limited number of samples; only one or two blades of a given design are tested so that no statistical distribution of production blade strength can be obtained. Therefore, although the tests do give information valid for the blade type, they cannot replace either a rigorous design process or the use of a quality control system for blade production.

Additionally, tests can be used to determine blade properties in order to validate some vital design assumptions used as inputs for the design load calculations. Finally, full scale tests give valuable information to the designers on how the structure behaves in the test situation and which structural details that are important and should be included in the structural models for design. Especially, valuable information is obtained if the blade is tested to failure.

According to DNV [3.7], it is required that the test program for a blade type shall be composed of at least the following tests in this order:

- Mass, centre of gravity, stiffness distribution and natural frequencies
- Static tests
- Fatigue load tests
- Post fatigue static tests

All tests should be done in flapwise direction towards both the downwind (suction) and upwind (pressure) sides and in edgewise directions towards both the leading and trailing edges. If it is important for the design, also a torsion test is needed in order to determine the torsional stiffness distribution. The tests are undertaken to obtain two separate types of information. One set of information relates to the blade's ability to resist the loads that the blade has been designed for. The second set of information relates to blade properties, strains and deflections arising from the applied loads.

All tests in a given direction and in a given area of a blade shall be performed on the same blade part. The flap- and edgewise sequence of testing may be performed on two separate blades. However, if an area of the blade is critical due to the combination of flap- and edgewise loading, then the entire test sequence shall be performed on one blade.

Failure types

Wind turbine blades can fail by a number of different failure and damage modes. The details of damage evolution will differ from one blade design to another. However, experience shows that, irrespective of specific blade design, several types of material-related and structural-related damage modes can develop in a blade. In some instances, these damage modes can lead to blade failure or require blade repair or replacement.

There can be many causes that a composite structure fails ultimately.

- Geometrical factors associated with buckling, large deflection, crushing or folding.
- Material factors associated with plasticity, ductile/brittle fracture, rupture or cracking damage.
- Fabrication related initial imperfections such as initial distortion, residual stresses or production defects.
- Temperature factors such as low temperature associated with operation in cold weather, and high temperature due to fire and explosions.
- Dynamic factors (strain rate sensitivity, inertia effect, damage) associated with impact pressure arising from explosion, dropped objects or similar.
- Age-related deterioration such as fatigue cracking.

A considerable amount of knowledge is required to assess how damage develops in a wind turbine blade and to design a blade against failure using analytical or numerical methods. Therefore, in order to validate the design, and to provide insight into possible damage modes and their severity, blades are sometimes tested to failure by full-scale testing. Fig. 3.2 shows sketches of the failure modes found in a wind turbine blade tested to failure [3.8].
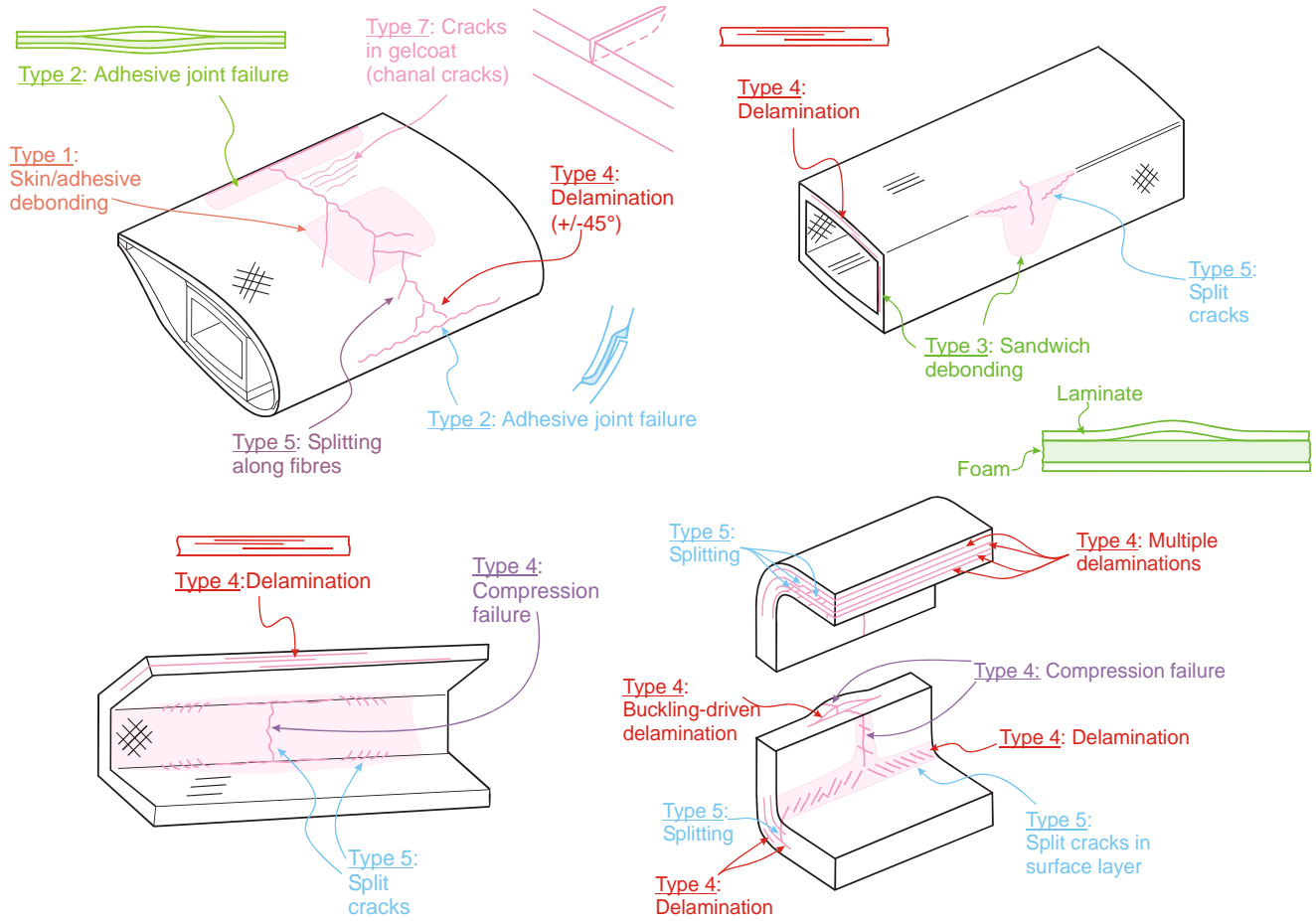
Figure 3.2: Sketches of observed failure modes in a wind turbine blade purposely tested to failure [3.8]; damages in the aeroshell and box girder.

4. Current design philosophy

Wind turbine blades are normally designed based on a deterministic design approach where safety is introduced by using characteristic values and partial factors as generally described in ISO 2394 [4.1]. According to the general wind turbine standard IEC 61400-1 [4.2] the following deterministic design format is used:

$$\gamma_n \cdot S\left(F_d\right) \leq R\left(f_d\right) \qquad (4.1)$$

where the load function $S(\cdot)$ transforms the applied load into forces or stresses in a specific cross-section of the blade and the resistance function $R(\cdot)$ transforms the material properties into resistance forces or stresses in the same cross-section. The design value for the load F_d and the design value for the resistance f_d are given by:

$$F_d = \gamma_f F_k \qquad (4.2)$$

$$f_d = \frac{1}{\gamma_m} f_k \qquad (4.3)$$

where F_k is the characteristic load which in ultimate limit state normally corresponds to a 50 year return period which again corresponds to the 98% quantile in the distribution function for the annual maximum load. In the fatigue limit state the characteristic load often corresponds to the mean value or a slightly higher quantile since a characteristic value for the turbulence intensity is used in the aeroelastic simulations to estimate the fatigue loads. The characteristic value for the material properties f_k is in the ultimate and fatigue limit state normally defined as a 5% quantile with a confidence interval on 95% using classical statistics. A description of how characteristic material properties can be estimated in both ultimate and fatigue limit state is given later in this section.

The partial factors γ_n, γ_f and γ_m used in (4.1), (4.2) and (4.3) corresponds to the following:

- γ_n : partial factor for consequences of failure
- γ_f : partial factor for loads
- γ_m : partial factor for materials

The method for introducing safety used in IEC 61400-1 and shown in equation (4.1) is in general good when the load and resistance functions are linear or close to linear. For nonlinear load and resistance functions the safety introduced by the method can vary significantly dependent on e.g. material properties, loading conditions and geometries. This effect can partly be taken into account by estimating the design resistance R_d by [4.3]:

$$R_d = \frac{R_k}{\gamma_m} \qquad (4.4)$$

where R_k is the characteristic load carrying capacity (5% quantile with 95% confidence) and γ_m is the partial factor for the resistance. Additionally, the load and resistance functions can be biased which will introduce either extra or less safety in the structure. The bias of the load and resistance functions should be taken into account in a reliability assessment and also be reflected in the partial factors.

Wind turbine blades can be designed based on the following standards / guidelines:

- IEC 61400-1 (3rd edition, 2005) [4.2], Wind turbines – Design requirements
- DNV-OS-J102 (2010), Design and manufacturing of wind turbine blades, offshore and onshore wind turbines [4.4]
- GL (2010), Guideline for the certification of wind turbines [4.5]
- IEC 61400-5 (draft, 2012) [4.6], Wind turbines – Wind turbine blades

IEC 61400-1 is a general design standard which specifies the general design requirements for all wind turbine components with the main focus on specifying the loading conditions for the wind turbine. In IEC 61400-1 the following four analysis cases should be considered:

- Ultimate strength (ultimate)
- Fatigue strength (fatigue)
- Stability (buckling)
- Deflection (deflection)

The design standards DNV-OS-J102 and IEC 61400-5 are specific standards for wind turbine blades, while GL 2010 includes an extensive section on blades to cover missing items of IEC 61400-1. Therefore additional analysis cases are specified such as inter laminar analyse and bond analysis. In table 4.1 the partial factors for the individual standards are compared and the ranges indicate that the partial factors vary dependent on e.g. the basic materials, manufacturing process, etc. The partial factors for the loading correspond to normal and extreme conditions. Special partial safety factors are available for e.g. abnormal conditions and transportation. It is important to note that the partial safety factors not necessarily can be directly compared due to different assumptions about calculation methods, uncertainties, etc. in the standards or guidelines.

Table 4.1: Comparison of partial factors for IEC 61400-1 [4.2], DNV-OS-J102 [4.4], GL 2010 [4.5] and IEC 61400-5 [4.6].

Design load case	IEC 61400-1	DNV-OS-J102	GL 2010	IEC 61400-5 Draft
Ultimate	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.30$	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.57\text{-}2.27$	$\gamma_f = 1.35$ $\gamma_m^{FF} = 2.21\text{-}2.65$ $\gamma_m^{IFF} = 1.69$	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m^{FF} = 2.25\text{-}2.71$
Fatigue	$\gamma_n = 1.15$ $\gamma_f = 1.00$ $\gamma_m = 1.20$	$\gamma_n = 1.15$ $\gamma_f = 1.00$ $\gamma_m = 1.32\text{-}1.90$	$\gamma_f = 1.00$ $\gamma_m = 1.49\text{-}2.35$	$\gamma_n = 1.15$ $\gamma_f = 1.00$ $\gamma_m = 1.34\text{-}1\text{-}96$
Buckling	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.20$	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.57\text{-}2.27$	$\gamma_f = 1.35$ $\gamma_m = 1.63\text{-}2.04$	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.63\text{-}2.45$
Deflection	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.10$	$\gamma_n = 1.00$ $\gamma_f = 1.25/1.35$ $\gamma_m = 1.10$	Requirements tower clearance	-

Characteristic Material Properties:
The characteristic value for the material properties f_k is in the ultimate limit state is in IEC 61400-1 defined as a 5% quantile with a confidence interval on 95% using classical statistics. The military handbook [4.7] uses a characteristic value specified as the 1% or 10% quantile with a confidence interval on 95%. The confidence interval can also be estimated using Bayesian statistic where no specific confidence interval is specified. However the method corresponds approximately to a confidence interval on 75%.

If a strength parameter X is assumed lognormal distributed, the characteristic value defined as a *p*-quantile with *q*-confidence can be defined by equation (4.5) if the coefficient of variation V is unknown and by equation (4.6) if the coefficient of variation is known.

$$x_{c,s} = \exp\left(m_Y - k_s s_Y\right) \tag{4.5}$$

$$x_{c,\sigma} = \exp\left(m_Y - k_\sigma \sqrt{\ln\left(1+V^2\right)}\right) \tag{4.6}$$

where the distribution parameters for $Y = \ln(X)$ which is normal distributed are given by:

$$m_Y = \frac{1}{n}\sum_{i=1}^{n}\ln(x_i) \tag{4.7}$$

$$s_Y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln(x_i)-m_Y\right)^2} \tag{4.8}$$

The parameters k_s and k_σ takes the *p*-quantile with *q*-confidence into account and are given by:

$$k_s = \frac{t_{n-1,q}\left(-u_p\sqrt{n}\right)}{\sqrt{n}} \tag{4.9}$$

$$k_\sigma = \frac{u_q}{\sqrt{n}} - u_p \tag{4.10}$$

where u_p and u_q is defined from the standard normal distribution using $u_p = \Phi^{-1}(p)$ and $u_q = \Phi^{-1}(q)$. $t_{n-1,q}$ corresponds to the non-central t-distribution. In table 4.2 are values for k_s and k_σ given for p=0.05 and q=0.95 for variable number of tests *n*.

Table 4.2: k_s and k_σ as function of *n* for quantile *p*=0.05 and confidence *q*=0.95.

n	k_s	k_σ
5	4.20	2.38
10	2.91	2.17
15	2.57	2.07
20	2.40	2.01
30	2.22	1.95
50	2.07	1.88
100	1.93	1.81
∞	1.65	1.65

Methodology described in the present section can be used directly for normal and lognormal distributed variables.

The characteristic value for the material properties f_k is in the fatigue limit state is in IEC 61400-1 also defined as a 5% quantile with a confidence interval on 95% using classical statistics. In the fatigue limit state it is often assumed that the number of cycles to failure are normal distributed on log-scale, see figure 4.1.
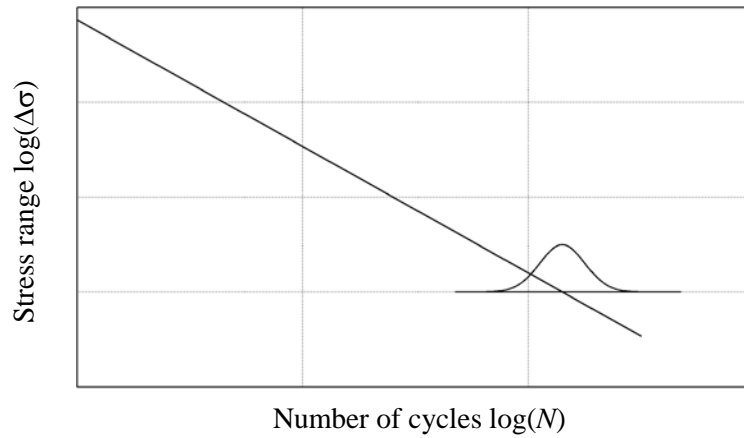
Figure 4.1. SN-curve with normal distribution.

In the log-log-space the mean SN-curve can be estimated using linear regression. The characteristic value for the regression line can then be estimated using classical statistics. More details on estimating the characteristic SN-curve can be found in e.g. [4.8] and [4.9].

5. Methods for reliability estimation

The reliability of a wind turbine blade can be estimated using reliability methods if a limit state function $g(\cdot)$ can be formulated [5.1]:

$$g(\mathbf{x})\begin{cases} > 0 & for \quad \mathbf{x} \in \omega_s \\ \leq 0 & for \quad \mathbf{x} \in \omega_f \end{cases} \tag{5.1}$$

where $\mathbf{x}$ denotes a vector of stochastic variables. ω_s and ω_f corresponds to the safe and failure set, respectively. The probability of failure P_F is given by:

$$P_F = P\big(g(\mathbf{X}) \leq 0\big) \tag{5.2}$$

The corresponding reliability index β is given by:

$$\beta = -\Phi^{-1}(P_F) \tag{5.3}$$

where Φ is the cumulative distribution function for the standard normal distribution. Reliability methods can in general be divided into the following four groups:

- First Order Reliability Methods (FORM)
- Second Order Reliability Methods (SORM)
- Monte-Carlo simulation
- Advanced simulation techniques

In the following are the individual methods shortly described. For a more detailed description the reader is referred to the literature.

First Order Reliability Method (FORM):
In FORM [5.1, 5.2, 5.3] the individual stochastic variables x in the limit state function are transformed into an uncorrelated, standard normal distributed space u. In this transformed space the limit state equation is approximated by a linear function. The Hasofer and Lind reliability index β [5.1] is then equal to the shortest distance from the origin to the failure surface in the transformed space. The point on the failure surface, which is closest to the origin, is denoted the β-point $\mathbf{u}^*$ and corresponds to the most probable failure point. Sensitivity measures for the individual stochastic variables can easily be obtained.

Reliability estimation using FORM is in general accurate when the failure surface in the u-space is relatively linear. However, for very nonlinear failure surfaces (due to nonlinear stochastic variables or nonlinear limit state function) the method will not provide accurate results.

Second Order Reliability Method (SORM):
In SORM [5.1, 5.2, 5.3] the individual stochastic variables are also transformed into an uncorrelated, standard normal distributed space as in FORM. In the transformed space, the limit state function is approximated by a quadratic function from which the probability of failure is estimated.

Reliability estimation using SORM is preferable to FORM when the failure surface in u-space is relative nonlinear. However, the method is also more computationally demanding.

Monte-Carlo simulation:
In Monte-Carlo simulation random realizations of the individual stochastic variables are generated in order to evaluate the limit state function. Based on N random simulations the probability of failure can be estimated from [5.4]:

$$P_F = \frac{1}{N} \sum_{j=1}^{N} I\left[g\left(\mathbf{x}_j\right)\right] \qquad (5.4)$$

Where the indicator function $I[\cdot]$ are defined by:

$$I\left[g\left(\mathbf{x}\right)\right] = \begin{cases} 0 & for & g\left(\mathbf{x}\right) > 0 \\ 1 & for & g\left(\mathbf{x}\right) \leq 0 \end{cases} \qquad (5.5)$$

The standard deviation on the estimated probability of failure can be estimated from:

$$s = \sqrt{\frac{P_F\left(1 - P_F\right)}{N}} \qquad (5.6)$$

Advanced simulation techniques:
The disadvantage with the FORM and SORM methods is that the methods do not always converge, especially for nonlinear limit state functions. Monte-Carlo simulation on the other hand, always converges to the correct probability of failure, if enough simulations are used. However, if the limit state function is time consuming to evaluate (e.g. a finite element model) and/or the probability of failure is very low, this method can be very time consuming to use. For these reasons more advanced methods are sometimes applied in order to estimate the probability of failure.

The general idea in the more advanced simulations methods is normally to exclude part of the failure region in order to concentrate the simulations to the most probable failure region. This approach has been used in e.g. Important Sampling [5.5] and Latin Hybercube sampling [5.6]. In Sub-set simulation [5.7] the probability of failure is determined as a product of conditional probabilities which are estimated using Markov chain Monte-Carlo simulation.

6. Reliability level

The target reliability level for buildings and bridges has been discussed in e.g. JCCS [6.1] and ISO 2394 [6.2]. The target annual reliabilities which are shown in table 6.1 are dependent on the cost of safety measures and the consequences of failure. In NKB [6.3] the target annual reliability is specified dependent on the expected consequences of failure and the failure type which can be ductile or brittle. These reliabilities are in general comparable to the values specified in ISO 2394.

Table 6.1: Target annual reliability index and probability of failure according to JCSS [6.1] and ISO 2394 [6.2].

Relative costs of safety measures	Consequences of failure			
	Small	Minor / Some	Moderate	Large
High cost of safety measures	ISO 2394: β^t=2.2, P_F=1.4·10^{-2}	JCSS: β^t=3.1, P_F=1.0·10^{-3} ISO 2394: β^t=3.0, P_F=1.4·10^{-3}	JCSS: β^t=3.3, P_F=4.8·10^{-4} ISO 2394: β^t=3.5, P_F=2.2·10^{-4}	JCSS: β=3.7, P_F=1.1·10^{-4} ISO 2394: β^t=4.1, P_F=1.9·10^{-5}
Moderate cost of safety measures	ISO 2394: β^t=2.9, P_F=2.0·10^{-3}	JCSS: β^t=3.7, P_F=1.1·10^{-4} ISO 2394: β^t=3.5, P_F=2.2·10^{-4}	JCSS: β^t=4.2, P_F=1.3·10^{-5} ISO 2394: β^t=4.1, P_F=1.9·10^{-5}	JCSS: β^t=4.4, P_F=5.4·10^{-6} ISO 2394: β^t=4.7, P_F=1.4·10^{-6}
Low cost of safety measures	ISO 2394: β^t=3.5, P_F=2.2·10^{-4}	JCSS: β=4.2, P_F=1.3·10^{-5} ISO 2394: β^t=4.1, P_F=1.9·10^{-5}	JCSS: β^t=4.4, P_F=5.4·10^{-6} ISO 2394: β^t=4.7, P_F=1.4·10^{-6}	JCSS: β^t=4.7, P_F=1.3·10^{-6} ISO 2394: β^t=5.1, P_F=1.7·10^{-7}

Failure of a wind turbine does normally have a small to minor consequence. Additionally, the risk of human lives is small especially offshore because persons normally are not close to the wind turbine. The optimal target reliability level can for this reason be determined by cost benefit analysis, where all the cost during the wind turbines design life is taken into account, see e.g. [6.4].

In Veldkamp [6.5] a cost benefit analysis was performed for the individual wind turbine components, see table 6.2. The optimal reliabilities are in the same range as the reliabilities estimated from JCSS and ISO 2394. In the wind turbine standards IEC 61400-1 and IEC 61400-3 no specific values for the target reliability level is given. However, the partial factors used in IEC 61400-1, corresponds according to [8.2] to an annual target reliability index β in the range of 3.1 to 3.5. This corresponds to an annual probability of failure P_F in the range of 1.0·10^{-3} to 2.2·10^{-4}.

Table 6.2: Annual reliability index and probability of failure estimated by cost benefit analysis [6.5].

Component	Reliability level
Blades	$\beta = 2.70$, $P_F = 3.5 \cdot 10^{-3}$
Tower	$\beta = 3.26$, $P_F = 5.0 \cdot 10^{-4}$
Hub	$\beta = 3.64$, $P_F = 1.3 \cdot 10^{-4}$
Nacelle	$\beta = 4.01$, $P_F = 3.0 \cdot 10^{-5}$

7. Uncertainty in material properties

In order to adopt probabilistic design a distribution function for the variation in the material properties is required as input data. For composite materials, considerable scatter is typically encountered for the key mechanical parameters.

The resistance of a composite structure can, along with the associated uncertainty, be modelled from the micro-, meso- or macro-scale as described in e.g. [7.12]. On the micro-scale variations in the fibre and matrix material are used together with variations in the manufacturing process to estimate the uncertainty in the material properties. On the meso-scale tests with plies / laminas are used for estimating the uncertainty in the material properties. On macro-scale, tests with composite components are used to estimate the uncertainty on the resistance of the composite structure.

For wind turbine blades, coupons are normally used to estimate the material properties and these are then through design models used to estimate the resistance of sub-components and the full-scale blade, see figure 7.1. However, according to IEC 61400-1 at least one full-scale blade test (not leading to failure) should be performed. In the resistance and reliability modelling it is important to take e.g. size-effects and new uncertainties introduced at higher scales into account. Especially, the effect of defects in the material and bonded joints should be considered with care. In the reliability modelling the effect of quality control during and after the manufacturing process should be taken into account.
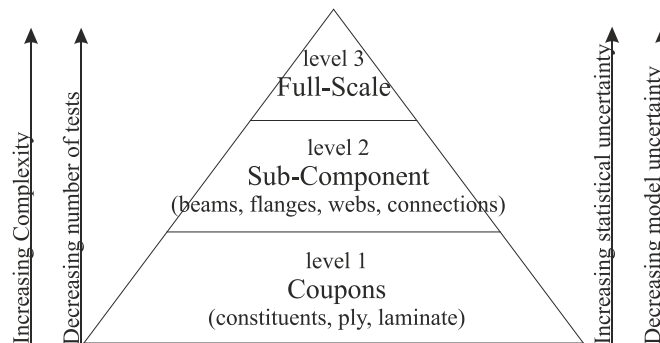

Figure 7.1. Illustration of tests performed for assessment of load bearing capacity of wind turbine blades [7.13].

The uncertainties related to the material properties can in general be divided into:

- Physical uncertainty due to natural variation of a quantity.
- Model uncertainty related to mathematical/physical models
- Measurement uncertainty due to imperfect measurements during tests.
- Statistical uncertainty due to imperfect knowledge / limited of tests.

The measurement uncertainty should include all uncertainties related to the test along with their influence on the measured properties. These uncertainties include, but are not limited to:

- Uncertainties in measuring devices.
- Variations in data acquisition and post-processing software.
- Variations in human processes such as specimen measurement and specimen set up in test rig.

General guidelines and testing standards aim to keep these uncertainties as low as possible. However, especially for composite material testing these are not always clearly defined. A quantification of measurement uncertainties for static tests on composites can be found e.g. in [7.8].

The uncertainties not taken into account should in general be identified and described. This is often uncertainties related to e.g. effect of temperature, humidity and UV-radiation.

In the production of the specimens various uncertainties related to the materials mechanical properties can be identified. It is in the following assumed that material for mechanical characterisation is manufactured as **specimens** in a **lot** (e.g. specimens from same infusion panel), for which a certain **batch** of constituent materials (roll of glass fabric, production batch of resin) was used. Several sources for this uncertainty can be identified, e.g.:

- Variation of material properties within specimen and lot
    - Variation of geometry within specimen. E.g. the original geometry of the final failure location is not exactly known (limited dimensions are measured in a specimen prior to testing). In composites, the internal geometry variables such as fibre exact alignment with the load, fibre undulations through the specimen thickness (at the failure location) are also not exactly known.
    - Inherent variability of production process, e.g. automated filament winding can give more consistent quality than manual laminate stacking
    - Resin composition/glass transition temperature are not uniform
        - due to mixing of components
        - due to local cure cycle
    - Fibre fraction is not uniform
        - due to fibre architecture
        - due to infusion/production method
    - Effects of time and environment, e.g. ambient temperature and relative humidity during handling
- Variation in properties within a batch
    - Production technology, e.g. glass-fibre thickness may vary along fibre length.
    - Chemical composition of fibre as well as matrix material can vary over production date (e.g. when using natural fibres).

The degree in which any of the above uncertainties influence the material property depends partly on the property itself. Fibre dominated elastic properties such as Young's modulus and Poisson ratio are typically not very sensitive to matrix variations or local fibre architecture, whereas strength is sensitive to fibre content as well as architecture, and fatigue life is probably sensitive to all of the abovementioned items.

In table 7.1 an overview is generated of typical uncertainty for specific material properties, see also [7.9]. The uncertainties are except from the Poisson ratio and a single stiffness component in general small (less than 5%). Higher uncertainties are specified in other references e.g. [7.9] and [7.10] for glass/polyester (hand lay-up). These uncertainties are listed in table 7.2. It is noted that reference [7.10] deals with composite material mainly used for ship structures. The higher uncertainties in [7.9] are perhaps due to larger variation in the manufacturing process, which perhaps are more representative for real application.

Table 7.1: Typical coefficients of variation (from static tests) for specific material properties.

Material	Loading	Direction	Strength	Stiffness	Poisson	Source	Remark
GFRP - UD	Tension	0°	6.0%	-	-	7.1	Data from several lots and probably batches
GFRP - UD	Tension	0°	3.1%	0.5%	-	7.2	5 adjacent specimen from same panel
GFRP - UD	Tension	0°	2.6%	4.5%	7.6%	7.3	15 specimens
GFRP - UD	Tension	0°	4.7%	2.6%	9.3%	7.4	Specimens from 7.3 + 15 additional specimens
GFRP - UD	Tension	0°	1.3%	2.9%	11.0%	7.5	4 specimens
CFRP Prepreg - UD	Tension	0°	4.0%	3.0%	8.0%	7.6	7 specimens, outer layer ±45° biax
CFRP Prepreg - UD	Tension	0°	5.0%	13.1%	12.0%	7.7	6 adjacent specimen from same panel, 4 UD layers

Table 7.2: Typical coefficients of variation for material properties.

Material property	Lekou & Phillippidis 2008 [7.9]	DNV-OS-C501 [7.10]

	Distribution	COV	COV
E_1 [GPa]	Weibull	0.089	0.05
E_2 [GPa]	Extreme Type I	0.148	0.10
G_{12} [GPa]	Gamma	0.249	0.10
v_{12} [-]	Weibull	0.187	0.10
X_T [MPa]	Weibull	0.151	0.05
X_C [MPa]	Lognormal	0.101	0.05
Y_T [MPa]	Extreme Type I	0.150	0.10
Y_C [MPa]	Extreme Type I	0.135	0.15
S [MPa]	Weibull	0.181	0.10

Estimating the fatigue properties and their variation are more complex than for ultimate loading. Normally tests are performed for different ratio's (R-ratio) between the minimum and maximum load in constant amplitude fatigue. However, a large scatter is often observed as described in the e.g. [7.1] where a large amount of fatigue tests are conducted for different lay-ups. Additionally, model uncertainty is introduced dependent on which SN-curve (semi-logarithmic or logarithmic) is applied to the test results, see e.g. [7.11].

8. Uncertainty in design models

In order to estimate the reliability of a wind turbine blade the uncertainty related to the mathematical models used in the design process should be known. These uncertainties are e.g. related to:

- Stresses and strains estimated by finite element analysis
- Local and global instabilities estimated by finite element analysis
- Assessment of ultimate failure by failure criteria
- Assessment of fatigue failure by failure criteria

The uncertainty related to the stresses and strains estimated by finite element analysis will be dependent on how detailed the model is. In JCSS [8.1] the uncertainty related to the load effect is given for a variety of structures within civil engineering. The uncertainties are in general assumed Lognormal distributed with a coefficient of variation of 5-20%, dependent on the complexity of the structure. Wind turbine blades have in general a very complex geometry and layered structure. However, the finite element models used are normally more advanced than the model used for most buildings. Additionally, the finite element model can be calibrated through the full-scale tests. In Tarp-Johansen [8.2] the model uncertainty related to the stress and strain estimation is assumed Lognormal distributed with a coefficient of variation of 3% for all wind turbine components (tower, blades and foundation). In GL [4.5] a deviation of ±7% for bending deflection, ±5% for natural frequencies and ±10% for strains are admissible when numerical models are compared to full-scale blade tests. Results from comparison of finite element models and sub-component or full-scale tests could provide more data which could be used to estimate the model uncertainty.
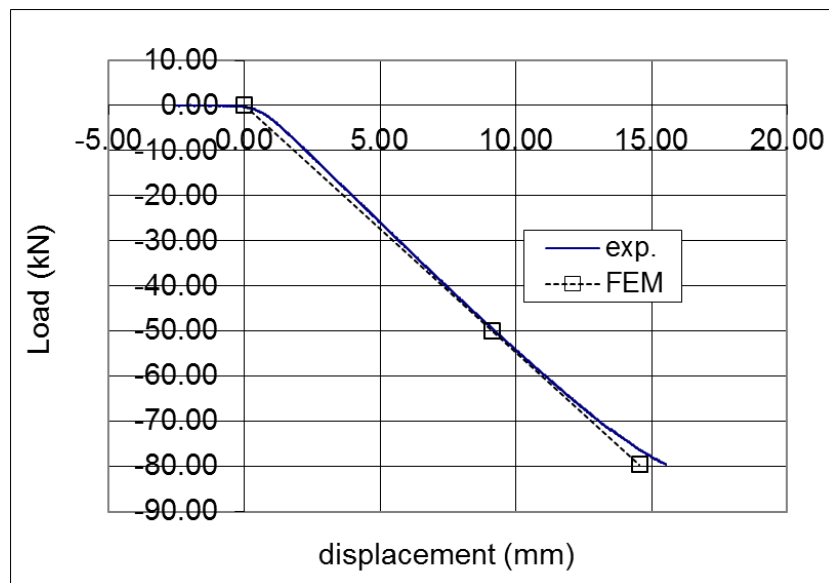

Figure 8.1: Comparison of estimation of deflection (numerical simulation) versus experiment.
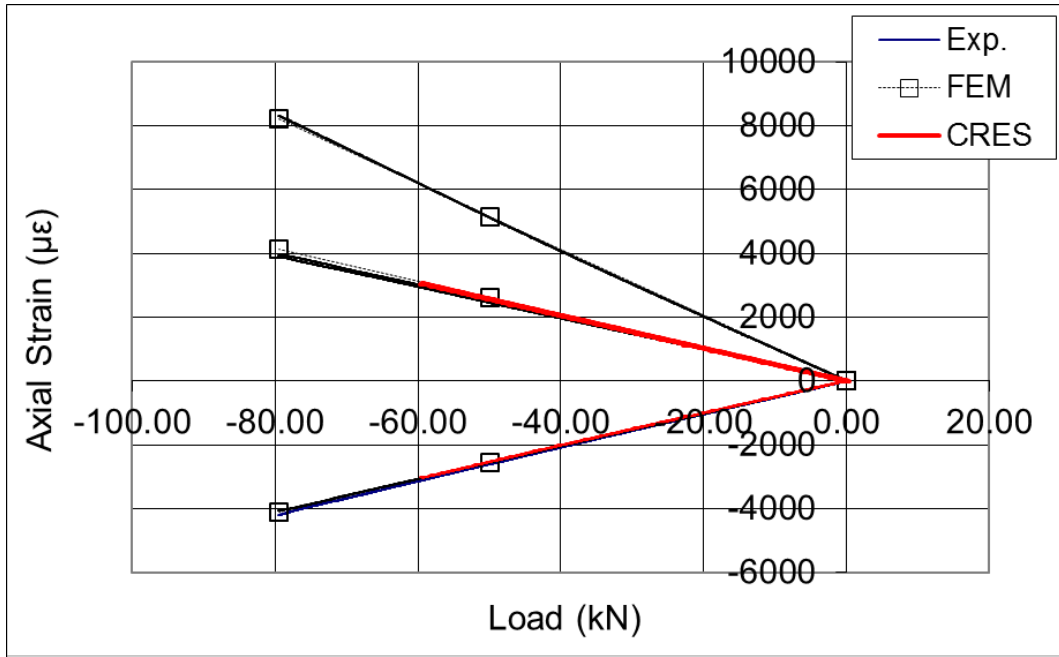
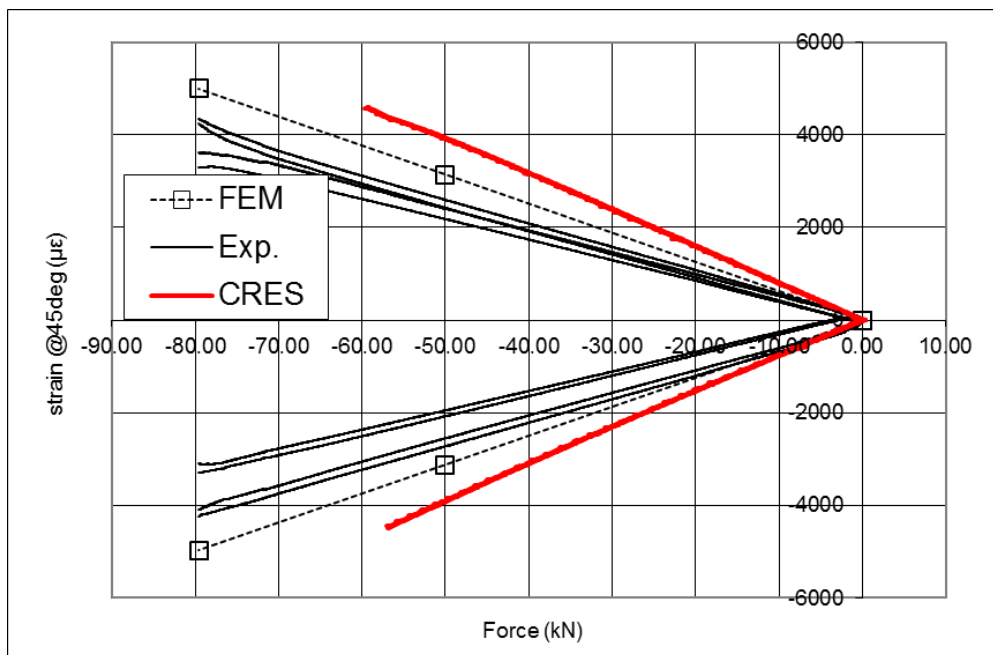Figure 8.2: Comparison of axial strain from FEM and experimental results.

Figure 8.3: Comparison of strain at 45deg with respect to the length of the beam.

Figure 8.1, 8.2 and 8.3 shows a comparison of numerical and experimental results derived from work performed within UPWIND project under work-package WP3 [8.3]. In the frame of UPWIND two sets of composite material beams were manufactured and distributed to several partners for 3- or 4-point bending tests. Numerical simulation was performed using information for the material as provided by the manufacturer of the beams and test results for the materials performed within the UPWIND project by WMC. In figures 8.1 and 8.2 numerical analysis results performed by CRES are marked as "FEM" and noted with dashed lines. The continuous lines denoted "exp." experimental data from tests performed by WMC are shown, while for Figs. 8.2 and 8.3 additional experimental results from an I-beam of the same batch tested by CRES are shown in red lines. For the axial strain (figure 8.2) a good agreement between experimental data and numerical simulations are obtained. However for the shear strain (figure 8.3) some deviation in the results is observed. It should be noted that the beam had a constant cross section along the length and for the above numerical simulation tuning on the material thickness was performed (i.e. the nominal thickness was used for the

reinforced material). Similar experience can be obtained for full-scale blades; however, the results are normally confidential. The uncertainty in the strain measurements are in general in the order of 2%.

During a research project PROFAR [8.4] a large number (37) of small blades of 3.4m length were tested to failure through static and fatigue tests by three laboratories (TUD, Risø and CRES) in order to determine among other issues the blade to blade variation. During this experimental campaign also information regarding the mass and stiffness properties of the blades were collected and statistically analysed in Jørgensen and Fahmüller [8.5]. The blades were manufactured by a single manufacturer using procedures that reflected the current technology used for manufacturing large blades at that time, i.e. hand lay-up. Det Norske Veritas (DNV) supervised the manufacturing procedure to attain the required high quality manufacturing process.

The coefficient of variation for the total mass of the blades was 2.1%. The coefficient of variation for the centre of gravity of the blade was 0.9%, i.e. even lower than that of the blade mass. Laboratory to laboratory variation in these measurements was judged negligible [8.5].

The first and second flapwise, as well as the first edgewise natural frequencies were measured along with the damping ratio for 32 of the blades. The experiments revealed a coefficient of the variation for the blades' natural frequency from 1.1% to 2.3% [8.5]. Some laboratory to laboratory variation should also be taken into account, since the testing procedure and equipment was not the same for all laboratories. The damping properties were measured for some of the blades (23) and showed a coefficient of variation of 13.7% for the first mode in the flap direction and 6.7% for the respective mode in the edge direction [8.5]. Since this variation is the result not only of blade to blade variation, but also laboratory to laboratory as well as testing conditions and analysis within each laboratory, the variation of the damping properties is not thought as inherent to the blades.

Finally the bending stiffness of the blades was estimated during the PROFAR experimental campaign through measurements of exhibited strain and load during initial static tests (not strength test) performed on each blade by the three laboratories. In Jørgensen and Fahmüller [8.5] it is reported that coefficient of variation of stiffness (EI) in the tensile and compressive side of the blade along the length of the blade (in the range 0.06R to 0.8R) varies from 6.8% to 15.7% depending on the strain gauge position. Yet, in the report it is noted that laboratory to laboratory variation is present in these figures, since if the results of each laboratory were treated independently a coefficient of variation below 10% would be seen for all measurement positions.

For composite materials a large number of failure criteria exist in order to estimate ultimate failure of the fibre or matrix material along with the laminate. The individual failure criteria have e.g. been compared in the world-wide failure exercise [8.6], [8.7] and [8.8]. These results show that even after tuning the individual failure criteria they all are subjected to large uncertainty and for some criteria also a significant bias. Failure of the blade is normally defined using first or last ply failure, where blade failure is defined when the first ply or last ply fails. However, real blade failure develops progressively through the individual plies and/or the individual components of the blade which is not currently taken into account. More research on development of accurate and reliable models for estimating blade failure should therefore be conducted. Since testing is an integrated part of wind turbine blade design the models can be calibrated for the dominating loading conditions in order to reduce the uncertainty and bias.

Failure of composite materials in fatigue is normally estimated from SN-curves and Miners rule for linear damage accumulation. However, Miners rule often over estimates [7.13] the fatigue resistance of composites. For welded steel details the uncertainty related to Miners rule is often according to [8.9] assumed Lognormal distributed with a coefficient of variation on 30%. For composite materials the uncertainty seems to be higher.

Results regarding fatigue tests from the large experimental campaign in the PROFAR project are presented in van Leeuwen et al. [8.10] and Heijdra et al., [8.11], see figure 8.4. The blades had failure either in a section near the root or in the aerodynamic part of the blade. The results include comparisons of blade fatigue tests in both flapwise and edgewise loading, with fatigue tests on specimens having the same laminate as that of blades. Variation in results includes material uncertainty, laboratory to laboratory variation as well as blade to blade variation.
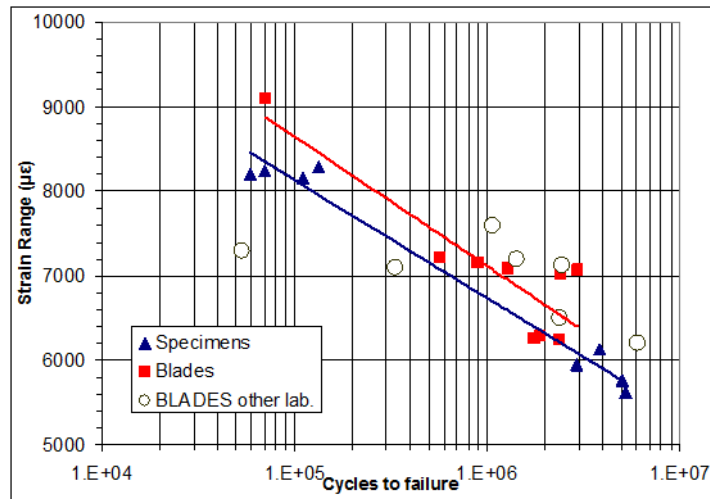
Figure 8.4: An example of the PROFAR results with blade tests. Blue triangles coupon tests conducted by CRES, Red squares tests conducted by CRES, Open circles tests conducted by other laboratories.

A lot of work is devoted to the modeling of composite materials under variable amplitude (fatigue) loading and the failure prediction. Some references comparing experimental results with theoretical estimations is giving a critical review on the various models used during each step of the prediction. See [8.12], [8.13] and [8.14].

9. Conclusions and future research needs

In the present report probabilistic methods for assessing the probability of structural failure for wind turbine blades are described.

The deterministic design procedure normally applied using the current design philosophy and documented through standards and recommendations is described.

Methods from structural reliability theory, which can be used to assess the probability of structural failure, are described. A large number of methods for estimating the reliability are available in the literature. These methods target different applications ranging from relatively simple limit state equations with a few stochastic variables to more complex limit states e.g. based on finite element analysis and a large number of stochastic variables. However, the target reliability level which should be applied for the wind turbine blades are often only known approximately.

In section 7 and 8 of the report the uncertainties related to the material properties and design models are considered in more detail. Although the progress has been substantial during the last 10 years regarding the material properties under static conditions, this is not the case for the fatigue properties where large uncertainties are observed both in testing and modelling. More advanced experimental methods have been developed on especially the coupon and full-scale level. However, sub-component tests are still under development along with application of the results in numerical modelling and reliability assessment. A major challenge for applying probabilistic design procedures in practical wind turbine design is to determine stochastic models for the individual uncertainties and model their influence based on physical mechanisms.

Future research should therefore focus on developing a systematic approach for assessment of the physical, model and measurement uncertainties related to wind turbine blade material properties, design models and manufacturing processes. The approach should focus on integrating coupon, sub-component, down-scaled and full-scale test results along with measurements from prototype and in-service wind turbines in order to update the uncertainties and the reliability level in a rational manner.

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