Structural Reliability of Wind Turbine Blades - DTU Orbit (31/12/2018)

**Structural Reliability of Wind Turbine Blades: Design Methods and Evaluation**

In the past decade the use of wind energy has expanded significantly, transforming a niche market into a practically mainstream energy generation industry. With the advance of turbine technology the search for more efficient solutions has lead to increased focus on probabilistic modelling and design. Reliability-based analysis methods have the potential of being a valuable tool which can improve the state of knowledge by explaining the uncertainties, and form the probabilistic basis for calibration of deterministic design tools.

The present thesis focuses on reliability-based design of wind turbine blades. The main purpose is to draw a clear picture of how reliability-based design of wind turbines can be done in practice. The objectives of the thesis are to create methodologies for efficient reliability assessment of composite materials and composite wind turbine blades, and to map the uncertainties in the processes, materials and external conditions that have an effect on the health of a composite structure.

The study considers all stages in a reliability analysis, from defining models of structural components to obtaining the reliability index and calibration of partial safety factors. In a detailed demonstration of the process of estimating the reliability of a wind turbine blade and blade components, a number of probabilistic load and strength models are formulated, and the following scientific and practical questions are answered:

a) What material, load and uncertainty models need to be used  
b) How can different failure modes be taken into account  
c) What reliability methods are most suitable for the particular task  
d) Are there any factors specific to wind turbines such as materials and operating conditions that need to be taken into account  
e) Are there ways for improvement by developing new models and standards or carrying out tests

The following aspects are covered in detail:

- The probabilistic aspects of ultimate strength of composite laminates are addressed. Laminated plates are considered as a general structural reliability system where each layer in a laminate is a separate system component. Methods for solving the system reliability are discussed in an example problem.  
- Probabilistic models for fatigue life of laminates and sandwich core are developed and calibrated against measurement data. A modified, nonlinear S-N relationship is formulated where the static strength of the material is included as a parameter. A Bayesian inference model predicting the fatigue resistance of face laminates based on the static and fatigue strength of individual lamina is developed. A series of tests of the fatigue life of balsa wood core material are carried out, and a probabilistic model for the fatigue strength of balsa core subjected to transverse shear loading is calibrated to the test data.  
- A review study evaluates and compares several widely-used statistical extrapolation methods for their capability of modelling the short-term statistical distribution of blade loads and tip deflection. The best performing methods are selected, and several improvements are suggested, including a procedure for automatic determination of tail threshold level, which allows for efficient automated use of peaks-over-threshold methods.  
- The problem of obtaining the long-term statistical distribution of load extremes is discussed by comparing the method of integrating extrapolated short-term statistical distributions against extrapolation of data directly sampled from the long-term distribution. The comparison is based on the long-term distribution of wind speed, turbulence, and wind shear, where a model of the wind shear distribution is specifically developed for the purpose.  
- Uncertainties in load and material modelling are considered. A quantitative assessment of the influence of a number of uncertainties is done based on modelled and measured data.  
- Example analyses demonstrate the process of estimating the reliability against several modes of failure in two different structures. This includes reliability against blade-tower collision, and the reliability against ultimate and fatigue failure of a sandwich panel. The results from the reliability analyses are then used for calibrating partial safety factors against a target reliability level.  

The main conclusions from the thesis are that a) the problem of estimating the reliability of wind turbine blades has been addressed in detail, and suitable methodologies for carrying efficient and robust reliability analysis have been identified, b) model uncertainties have a very high influence on the reliability estimate, and an effort to reduce model uncertainties can be rewarded with improved structural reliability or lower safety factors, and c) wind turbine design using present state-of-the-art models and standard safety factors results in sufficiently safe structures, and in some cases the actual reliability exceeds the assumed sufficient reliability levels significantly.

Aspects that need to be covered in further work are investigating the influence of defects, studying the fatigue properties of composites and defining physical models for fatigue damage accumulation, making risk-based decision analysis possible by including cost measures, quantification of uncertainties, and further improving the knowledge on turbine loads, including turbine controller behaviour, extreme operational events and frequency of faults, and assessment of the wind field across the entire rotor.

**General information**

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