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Spatial reliability analysis of a wind turbine blade cross section subjected to multi-axial extreme loading

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This paper presents a methodology for structural reliability analysis of wind turbine blades. The study introduces several novel elements by taking into account loading direction using a multiaxial probabilistic load model, considering random material strength, spatial correlation between material properties, progressive material failure, and system reliability effects. An example analysis of reliability against material failure is demonstrated for a blade cross section. Based on the study we discuss the implications of using a system reliability approach, the effect of spatial correlation length, type of material degradation algorithm, and reliability methods on the system failure probability, as well as the main factors that have an influence on the reliability.

1. Introduction

Wind turbine blade design loads are usually estimated with aeroelastic simulation tools. Here the turbine structure, represented by a beam finite element model [1], is subjected to random, dynamically varying environmental conditions. The outcome is the random loads obtained in terms of beam section forces and moments. The loading direction at a given time is defined by the orientation of the resultant of the section moments. Since the airfoil-shaped regions of wind turbine blades are not symmetric the blade strength will be dependent on the loading direction. It is therefore important to identify the most critical loading directions and base the blade design criteria on the structural performance in these directions. While sufficient for predicting the global behaviour of the structure, the beam fintie element modelling level does not provide information about the stress field at the material level. A more advanced approach is to combine the aeroelastic simulation tools with a finite element based cross-section analysis tool [2,3], where local stress design limits can be evaluated at multiple locations within a cross section and under different loading directions. The most critical loading direction does not necessarily coincide with the direction where the highest stress is observed. The random loading and the directional dependence of the material strength imply that for different load directions the likelihood of exceeding the ultimate strength will differ.

Structural reliability analysis provides the opportunity to take into account the inherent variability in both loads and material properties, and finding the most likely combination of factors that will result in failure. Previous studies on structural reliability of wind turbine blades exist in the literature, for example [4,5], which demonstrate a reliability analysis of a blade section, and [6], where the reliability along a line on the main spar of the blade is analyzed. In the aforementioned studies, the blade is subjected to pure bending moments in the flapwise direction, and system reliability effects are not taken into account. In the current article, we present a methodology for carrying out structural reliability analysis of wind turbine blade cross sections which, compared to previous studies, adds several novel elements: (1) the effect of loading direction by means of a probabilistic multiaxial extreme load model is considered; (2) the blade section is considered as a reliability system and it is shown how the failure probability for the entire section can be estimated by means of a system reliability analysis; (3) we demonstrate how spatial correlation of material properties can be taken into account and investigate the effect of different correlation lengths on the system reliability estimates.

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2. Problem definition

A reliability analysis with the features defined in the previous section requires a number of input models and variables:

- Structural response model (defining the stress within the section as function of section geometry, composite layup, material properties and loads)
- Limit state function (definition of failure and a function indicating the state of the structure)
- Stochastic load distribution model and corresponding random variables describing the load distribution
- Material strength model and stochastic variables describing material property distributions
- Uncertainty variables (accounting for inaccuracies in the models and inputs)
- A definition for the dependencies between input variables

In the following sections, we introduce the necessary models and explain the procedures for defining the probability distributions of the input variables. Due to possible ambiguity in the terms used (where e.g. components can both refer to components in a reliability system or vector components), throughout the paper we denote terms with possible double meaning by using a two-word description, as follows:

- *finite element* for the elements in a finite-element structural model;
- *system component* for the components in a reliability system;
- *component reliability* refers to the reliability of a component in a reliability system
- *load component* for vector components of structural loads defined in a Cartesian coordinate system;
- *vector component* for the components of a vector which does not represent loads, e.g. importance factors from reliability analysis;
- *structural component* for a major part in a wind turbine structure, e.g., a wind turbine blade or a part of a blade.

2.1. Limit state function

The standard approach to reliability analysis requires defining the state of the structure in terms of a vector of input random variables $\mathbf{X}$ and a scalar indicator function, the so-called limit state function $g(\mathbf{X})$, where $g(\mathbf{X}) \leqslant 0$ indicates structural failure. This broad definition of the limit state function allows representing complex system problems with multiple failure mechanisms (e.g. through a finite-element model). However, the scalar definition of the function means that a single output is produced for any combination of input variables. As a result, the limit state function value can provide information for only one failure mode at a time. Setting up a reliability model with multiple failure mechanisms can be done with two system reliability approaches:

(1) A “global” limit-state function can be designed such that it incorporates all failure modes. The output of the global limit state function will reflect the failure mode which results in the lowest safety margin. Probability integration over the failure domain defined by the “global” limit-state function will directly compute the system failure probability. However, such a limit state function may be very nonlinear, discontinuous or non-differentiable, which prevents the use of simple gradient-based reliability methods. Instead, the system failure probability can be computed using simulation-based approach (e.g., Crude Monte Carlo [7], Asymptotic Sampling [8], Adaptive Importance Sampling [9]).

(2) A separate limit-state function is defined for each failure mode of interest. The overall failure probability is computed as the joint failure probability of all limit states by treating each of the failure modes as a component in a reliability system. For a blade cross section, the section area is divided into a set of sub-divisions (e.g., individual finite elements in a finite element model), and each sub-division is treated as a system component in a reliability system.

Both approaches given above represent a spatial-reliability problem solved in a system reliability context. In the following sections, we discuss the calculation of the system failure probability for a blade cross section using both a Monte Carlo-based technique as well as a component-reliability based approach.

2.2. Section model

For the purpose of the study we use the Technical University of Denmark’s (DTU) 10 MW reference wind turbine [10] with rotor diameter of 178.3 m and hub height of 119.0 m[3]. The analysis is based on a finite element model of the cross section located at 62.4m radial position on the 86.4 m long blade. The finite element model is implemented in the specialized cross section modelling software BECAS [2], using 9004 finite elements with approximately 44,000 nodes. The choice of radial location for analysis is dictated by the distribution of the ratio between material capacity and loading under operation, which is almost constant from 0 m to 65 m radial distance. Thus the 62.4m radial position is towards the end of this plateau, and also coincides with the blade region which is subjected to the highest aerodynamic pressure.

The geometry of the cross section is shown on Fig. 1, and a more detailed view of the region where the spar cap joins the shear web is shown on Fig. 2. The analysis focuses on the composite materials in the section, namely uni-, bi- and tri-axial glass-epoxy laminates referred to as Uniax, Biax and Triax, respectively. An epoxy-based adhesive and balsa wood sandwich core material are also present in the section, however they are not considered in the present study where ultimate failure of fiber composites is chosen as the main focus. The sandwich core will carry some transverse shear stresses, however for typical blades these stresses are relatively small unless a very large non-linear deformation of the cross section occurs [11]. In cases where the failure of sandwich core is a relevant problem as in e.g. [12], the same procedure as discussed here can be applied. A detailed description of the cross section design is available in [10]. We assume typical elastic properties for the laminates under consideration. The values of the elastic properties for all materials in the cross section are available in [10]. Table 1 lists the elastic properties for the uni-axial and bi-axial materials which are the only materials analyzed in details in the remainder of this paper. The stiffness and strength values in Table 1 are given in the local material coordinate system, which as illustrated on Fig. 3 is individual for each material layer. The material is assumed to be linear elastic and effects from geometrical and material nonlinearities are not taken into account. Nonetheless, the progressive failure analysis approach presented here is also applicable when working with geometrical and material nonlinear models as well (see [13,11] for example applications). The material property distributions used in the present study are based on coupon tests, and as a result they only represent the uncertainty due to small-scale variations, and do not take large-scale defects into account. Large-scale defects invoke different failure mechanisms and in general need to be treated as sepa-

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[3] Detailed information on this turbine is available online: http://dtu-10mw-rwt.vindenergi.dtu.dk.