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Defect distribution and reliability assessment of wind turbine blades

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ABSTRACT

In this paper, two stochastic models for the distribution of defects in wind turbine blades are proposed. The first model assumes that the individual defects are completely randomly distributed in the blade. The second model assumes that the defects occur in clusters of different size, based on the assumption that one error in the production process tends to trigger several defects. For both models, additional information, such as number, type, and size of the defects, is included as stochastic variables.

In a numerical example, the reliability is estimated for a generic wind turbine blade model both with and without defects in terms of delaminations. The reliability of the blade decreases when defects are included. However, the distribution of the defects influences how much the reliability is decreased. It is also shown how non-destructive inspection (NDI) after production can be used to update the reliability for the wind turbine blade using Bayesian statistics.

1. Introduction

Calculation of the load-carrying capacity for wind turbine blades has previously been studied mainly from a deterministic point of view; see, e.g., [1,2]. However, significant variation in the load-carrying capacity can be observed, which to some extent can be caused by physical variations in the material properties. However, local production defects in the blades, which may arise from minor errors in the manufacturing process, also influence the load-carrying capacity. During operation, damage from impacts and aerodynamic loading of the blade may also influence the load-carrying capacity. The influence of variations in the material properties has been studied in [3], where different methods for determination of the probability of failure for wind turbine blades are also described.

Production defects mainly influence the load-carrying capacity through the following three parameters:

- type of defect,
- size of defect, and
- position of defect.

The influence of these parameters on the ultimate load-carrying capacity has been studied in the research project SaNDI, which focuses on sandwich structures for ships; see [4–6]. In [6], an experimental study was performed using sandwich panels loaded in compression and containing a delamination placed centrally. The results show that small delaminations have no influence on the failure load in compression, whereas larger delaminations reduce the failure load significantly. A more or less similar study was performed in [5], in which three different positions of the delamination (center, corner, and edge) were also investigated. The position of the delamination has a significant influence on the failure load.

In order to ensure that local production defects do not lead to failure of a wind turbine blade during operation, a damage-tolerant approach could preferably be adopted in the design process; see, e.g., [7]. In damage-tolerant design, it is verified that the structure can withstand the design load even though it contains a certain amount of damage.

In order to avoid larger production defects in wind turbine blades, quality control by non-destructive inspection (NDI) techniques such as visual inspection or ultrasound scanning should be performed after production. However, the NDI is not perfect, and remaining uncertainties due to production defects should be captured by partial safety factors on the material properties [8]. In practical blade manufacturing, NDI is frequently followed by destructive inspection and repair, if larger defects are detected. Such destructive inspection is used as a measure to better determine the type and size of the defect before estimating the extent of the repair as well as a basis for calibration and control of the NDI. In the present paper, we will not go into details of possible destructive inspection following NDI.

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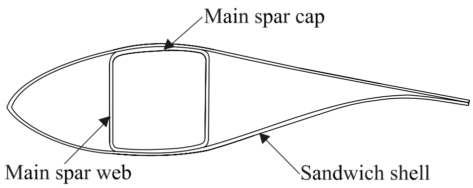

Fig. 1. Cross-section of wind turbine blade.

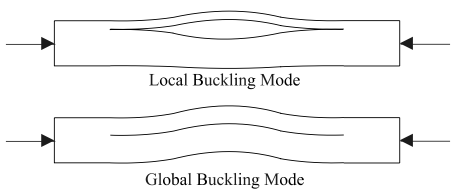

Fig. 2. Local and global buckling modes for delamination.

Information about production defects such as type, size, position, and number are in general impossible to obtain from blade manufacturers due to confidentiality. Additionally, such information is also highly dependent on, for example, the production process, blade geometry, and the training of personnel. However, in this paper we propose a general stochastic model for the distribution of production defects in wind turbine blades and a reliability-based approach to assess the importance of defects. The models can then later be calibrated and adjusted so that they better represent the distribution of production defects observed by the individual blade manufacturers.

The influence of delaminations on the load-carrying capacity of a wind turbine blade has been studied in a numerical example, and a method for reliability assessment of blades containing defects is presented. The estimated reliability of a generic blade model is in a numerical example updated using a Bayesian approach with the information obtained by NDI of the blade after production. The main objective of the numerical example is to identify the parameters which most influence the reliability when defects and damage tolerance are taken into account.

For purposes of simplicity, only one type of production defect (delaminations) has been considered in this paper. A typical cross-section of a wind turbine blade is shown in Fig. 1, and only the main spar is considered in the present study. However, the models and methods presented are general and can be adopted for other productions defects and other parts of a wind turbine blade.

2. Production defects—delaminations

Delaminations are areas of poor or no bonding between adjacent plies. They can be caused by air traps, a poor infusion of resin in the given area, or similar, dependent on the production process. For prepreg, the delaminations can also be due to a poor consolidation during curing. The delaminations will mainly reduce the compression strength of the wind turbine blade as the critical buckling load is reduced [9]. If the delamination is placed near the outer or inner surfaces of the laminate, the delamination may induce local buckling of a group of plies; see Fig. 2. If the delamination is placed near the centre of the laminate, the strength reduction will be caused by global buckling of the laminate; see Fig. 2 [10].

The influence of delaminations on the ultimate compression strength has been studied in [10,11] for glass fiber reinforced polymer (GFRP) and in [4,6] for sandwich structures exposed to different load cases. The main parameters which influence the strength reduction are the size of the delamination and the through-thickness position. But also other parameters such as the stacking sequence can influence the strength reduction. In the following, a delamination is modelled as a two-dimensional surface because it occurs between two plies in the laminate. The shape of the delamination is for purposes of simplicity assumed circular, with diameter s; see Fig. 3. The diameter s is modelled as a stochastic variable, and in this study the diameter is assumed to follow an exponential distribution; see Eq. (1). The exponential distribution is adopted because it gives a high probability for obtaining small defects and a low probability for obtaining large defects.

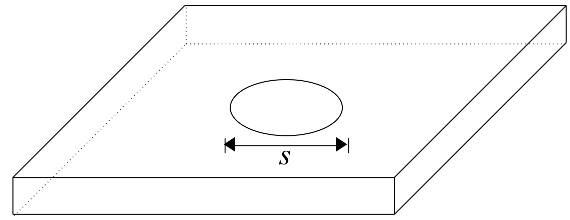

Fig. 3. Planar circular delamination with diameter s.

$$F_S(s) = P(S \le s) = 1 - \exp(-\chi_S s), \quad (1)$$

where S denotes a stochastic variable for the defect size and s denotes the corresponding deterministic defect size. χ_S is the intensity parameter for the diameter s which has a mean value of $1/\chi_S$.

3. Distribution of defects

In the following, two stochastic models for the distribution of defects in wind turbine blades are proposed. The distribution of defects for the two models is illustrated by a numerical example with the main spar for a wind turbine blade.

Model 1: *Completely random distribution of defects*

As previously stated, the position of defects in wind turbine blades has a significant influence on the reduction in load-carrying capacity. In this section, a stochastic model for the generation of completely random defects in a wind turbine blade is proposed in order to model the defects after production; see, e.g., [12,13]. The model is general and can later be adjusted to represent a specific manufacturing process.

In order to generate completely random defects, it is assumed that the blade can be considered as a planar two-dimensional region. For most defects, this will be an appropriate assumption, since defects tend to occur in a layer or in the interface between two layers. Adopting the assumption that the blade should be a planar region does not prevent modelling the general curvature and twist of a wind turbine blade. However, it is assumed that the blade component considered can be stretched and represented by a planar region; see Fig. 4. The position of each of the defects in thickness can next be modelled as a stochastic variable, by which only a two-dimensional model is adopted, which significantly reduces the complexity.

The completely random distribution of defects is based on the following two assumptions [12,13].

(i) The number of defects in region A with area $|A|$ follows a Poisson distribution.
(ii) The distribution of the n events in region A is an independent random sample from a uniform distribution on A.

The first assumption, (i), gives the following Poisson distribution for the number of defects n in region A.

$$P_{N_{|A|}}(n) = \frac{(\lambda|A|)^n \exp(-\lambda|A|)}{n!}, \quad (2)$$