Measurement uncertainty of fatigue properties and its effect on the wind turbine blade reliability level

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1. Introduction

Wind turbine rotor blades are large composite structures performing most of their design life under random cycle loading patterns. Material properties of the building ply exhibit also variability. In order to assure a safe and cost effective design, uncertainty related to the basic variables should be quantified and taken into account in design calculations. The rational way to deal with uncertainty of engineering structures is addressed in the field of structural reliability.

Reliability analysis of wind turbine rotor blades under variable amplitude loading has already been performed in the past [1]-[6]. The main effort, however, was put on the uncertainty quantification related to the environmental conditions e.g. the wind speed and turbulence as well as the statistical treatment of the sectional stress resultants and less with the uncertainty on the material properties. Moreover, when fatigue properties were considered as random variables only part of the uncertainty was quantified namely the physical and statistical uncertainty related to the limited sample size of experimental tests. Measurement uncertainty was totally ignored. This fact is also reflected in relevant standards, since only advances in statistical treatment of the loads have already been adopted into the IEC 61400 series. Regarding the materials for wind turbine blades, the available standards for composite materials do not provide any indication of the measurement uncertainty obtained through application of the experimental method and therefore, this is not considered in the design guidelines and standards for the blade design. This leads the latter to introduce partial safety factors, which are based on engineering judgement rather than experimental evidence.

Here in, for the first time, measurement uncertainty for the fatigue properties of the composite material is quantified following principles of metrology and based upon appropriate experimental data. This information is of high importance if comparisons are to be conducted between candidate materials or the effect of a parameter whether environmental or other is to be sought.

2. Approach

First, the procedure for estimation of the measurement uncertainty for the fatigue properties estimation of composite materials is developed. The methodology is applied on relevant experimental data for typical materials used in wind turbine blade manufacturing. To evaluate the effect of the measurement uncertainty on the wind turbine blade probabilistic methods are employed, to calculate failure probability at the ply level on several locations of a 10MW wind turbine blade. Several model uncertainties related to the fatigue analysis are also considered in the light of the results of the InnWind.Eu project [7]. The influence of each of the considered uncertainties examined directly on the failure probability at the ply level of the blade structure is further discussed.

3. Main body of abstract

In more detail, the procedure of measurement uncertainty quantification is developed for uni-axial tests, performed in force control, under normal ambient conditions with respect to temperature and humidity. The methodology takes into account uncertainties due to (i) the test instruments (load cell, strain gauge, resolution of cross-sectional measuring instruments etc.), (ii) the specimen itself (dimensions, tolerances etc.), (iii) the test procedure (standard's recommendations, zeroing, digitizing etc.) and (iv) the test environment. The stochastic nature of the material properties is considered by means of experimental data typical for the manufacturing of wind turbine rotor blades, while quantification of the measurement uncertainty on material properties relies on the principles of metrology [8]. The estimation of the measurement uncertainty is presented for the basic material parameters extracted through these tests, namely the constant and the slope derived for the S-N curves, i.e. on the derived stress against allowable number of cycles. The S-N curve is represented by the usual equation $S=CN^{B}$. Relevant standards as the ISO 13003 for the estimation of fatigue properties for composite materials do not provide information on building the uncertainty budget. Yet, this information is significant if comparisons are conducted between different data sets, for example to prove material equivalence and use available larger databases as reference, or if the effect of a particular parameter on the material property is sought, such as environmental effects or secondary manufacturing alternatives. Moreover, measurement uncertainty estimation is necessary if one is interested in evaluating the material inherent variability in terms of spatial property distribution or manufacturing repeatability on the laminate level.

To identify the role of measurement uncertainty on the probability of failure of the blade, the reliability level under variable amplitude loading is estimated based on the enhancement of probabilistic analysis tools developed for application on wind turbine blades in Bacharoudis & Philippidis [9] and Lekou & Philippidis [10]. The application is performed on the InnWind.Eu reference 10MW wind turbine blade with 90m length. The probability of failure against variable amplitude fatigue loading is estimated at the material ply level on several locations on each section of the blade. Sensitivity analysis is performed on the fatigue analysis details with respect to the final reliability estimation, such as the strategy when applying the rainflow counting method or the failure criterion used for the fatigue estimation.

Modelling uncertainty related to the fatigue analysis is also included by results of [7]. Various sources of uncertainty were considered including (i) the structural model, (ii) the calculation method of the stresses, (iii) the rainflow counting method (including parameters such as the bin size), (iv) the calculation of the damage from a pair of stress mean and amplitude and (v) the load modelling.

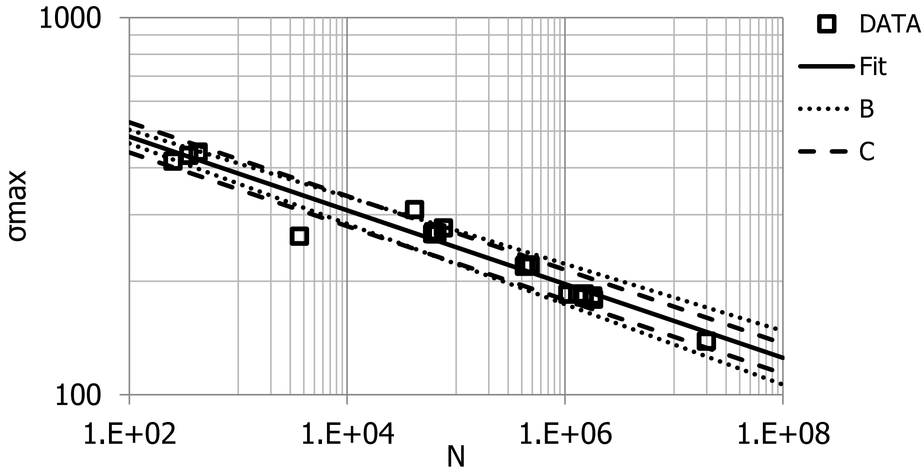

Fig1: Effect of the measurement uncertainty on S-N curve.

As an example the effect of measurement uncertainty on the derived S-N curve can be seen in Fig. 1, represented by S=CN^B. The dotted curves 'B' and dashed curves 'C' provide bounds (upper and lower) considering two standard deviations for each parameter respectively, comparable to the extended measurement uncertainty used in metrology applications.

Moreover, the influence of the uncertainty related to structural analysis theories directly on the fatigue reliability estimations at multiple locations of a blade section can be seen in Fig 2. Due to high fluctuations in failure probability value (P_f), the reliability β index value derived by P_f=Φ(-β), where Φ is the standard normal distribution, was used to depict the results. Two cases are considered in this example by altering the model uncertainty to represent the uncertainty of structural models estimation. This structural model uncertainty is varied between 5% and 35%.

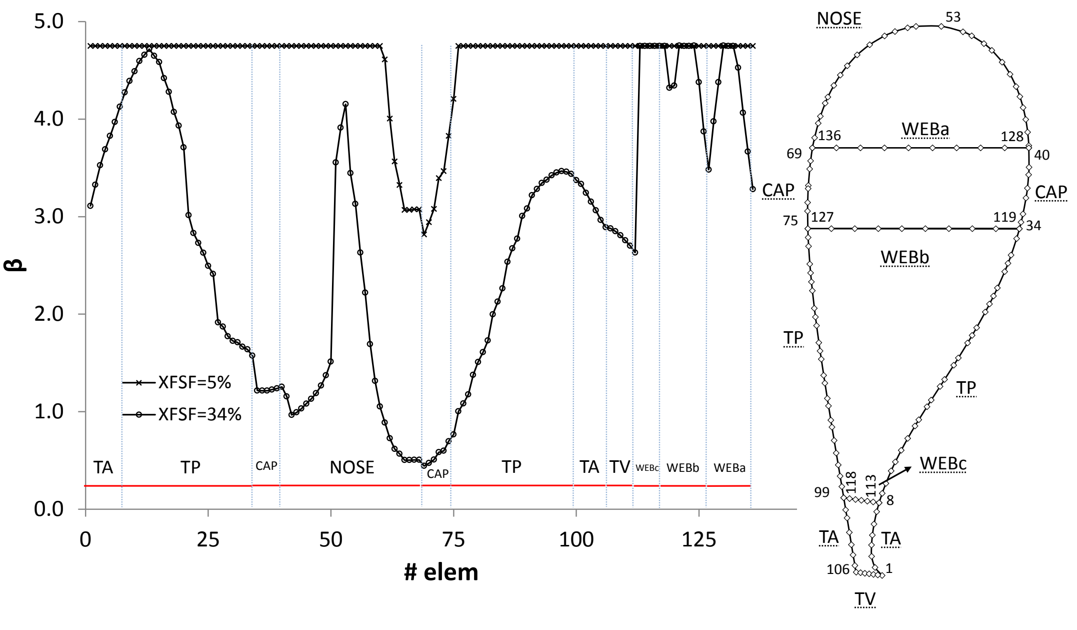

Fig 2: Effect of model uncertainty at the blade section

4. Conclusions

Measurement uncertainty takes into account all the possible sources of uncertainty relevant to the experimental determination of fatigue properties. This gives the advantage of rationalizing uncertainty quantification based on experimental evidence and not only in engineering judgment.

In the derivation of the uncertainty budget, an effort is made to identify and to incorporate all the testing parameters with an important contribution to the total uncertainty, including the accuracy in the coupon geometric properties measurements, the uncertainty resulting from the application of the regression for the S-N curves, the accuracy of the load measurements, etc. Estimations of the measurement uncertainty from composite material test result database are presented and results reveal a high uncertainty magnitude.

Introduction of the uncertainty in the fatigue failure model for the composite materials has a strong effect on the reliability results. Improving failure models for composites and thereby reducing the uncertainties will have a positive impact on the blade design.

By quantifying the individual uncertainty sources incorporated into the design of the blade, one gets a clearer picture of those (epistemic ones) that should be reduced by additional effort, so that the target reliability level is maintained and the use of materials optimized on the structure.

5. Learning objectives

The magnitude of measurement uncertainty in fatigue results for composite materials used in wind turbine rotor blades is estimated through a dedicated developed procedure. The effect of this uncertainty is pictured in the results of the reliability estimations directly on the blade at the ply level. The methodology developed, facilitates obtaining needed information for comparing different material candidates and/or manufacturing procedures for composite materials on blades.

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