Assessment of extreme stresses and deflections on wind turbine blades with stochastic material properties using statistical extrapolation methods

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Abstract. Since the introduction of the 3rd edition of the IEC Standard 61400-1, designers of wind turbines are required to apply statistical extrapolation techniques, to estimate the extreme (ultimate) load values corresponding to fifty-year return period. In the present paper, the certification procedure is assessed under the uncertainty of the material properties using simulated load time series of the NREL 5MW Reference Wind Turbine. The uncertainty of the material properties is introduced in the elastic properties of the composite blades by using input data from the OptiDAT composite material database. Comparison of the estimated extreme loads and deflections of the blades as well as maximum stresses, also in connection to the Tsai Wu failure criterion, is performed for different material sets. It is found that the variability of the material properties does not affect the estimated ultimate flapwise moments (difference <1.5%) but affects the maximum flapwise deflection (differences ~8%). It is concluded that for the levels of variation considered in the composite material properties, the coefficient of variation of the extreme stresses and the Tsai Wu failure criterion are in the order of 2% and 8% respectively.

1. Introduction
Part of wind turbines’ certification loop concerns the estimation of extreme loads corresponding to a 50-year return period. Because ultimate loading is usually driving the blade design, estimation of extreme loads is a decisive step in the design verification procedure. Due to the stochastic nature of the wind inflow, wind turbine extreme loads can only be obtained through statistical processing, and thus the resulting values of loads depend strongly on the applied method. In the current version of the IEC Standard 61400-1, 3rd edition (2009) [1], the statistical process for deriving extreme loads is linked to the Design Load Case (DLC) 1.1 that scans the full range of power producing wind speeds under Normal Turbulent inflow conditions. The procedure starts by dividing the power producing range of wind speeds into bins and proceeds with the following steps: a) for every wind speed bin a number of
10min aero-elastic simulations are performed, b) peak loads are extracted from these 10min simulations and c) a probability distribution function is fitted to the above peak-load data, which by extrapolation provides an estimate of the extreme load for the 50 years specific period.

2. Objectives
The objective of the present work is to assess the effect of the variability of the blade structural properties on the extreme blade flapwise moment, the blade tip flapwise deflection, the maximum stresses and the Tsai Wu failure criterion, in the context of the IEC standard.

3. Methodology
3.1. Material properties
In the present context, composite material properties are considered stochastic and they have been sampled from the OptiDAT database [2]. The database contains extensive material properties and load data from static/strength and dynamic/fatigue tests performed by the University of Patras in the framework of EU and National research projects. The tensile modulus of elasticity $E_1$ along the direction of the fibres, the tensile modulus of elasticity $E_2$ vertical to the direction of the fibres, the major Poisson ratio $\nu_{12}$ and the in-plane shear modulus of elasticity $G_{12}$ are found to follow a log-normal (LN) distribution, as shown for example in the cumulative distribution function (CDF) plot of the $E_1$ elasticity in Figure 1(a). The coefficient of variation (COV) of the stochastic set of material properties is of the order of 10%. Along with the stochastic set of data a reference set of material properties is also defined from the mean values of the OptiDAT database.

The wind turbine considered in the present analyses is the NREL 5MW Reference Wind Turbine. Equivalent integrated beam properties for the blades of this turbine are generated using the in-house tools PRE-THIN [3] and THIN [4], both based on Classical Lamination Theory. They take as input the composite material properties and information about the airfoil geometry and the stacking sequence of the composite plies over different cross sections of the blade and provide distributions of integrated beam-like properties along the blade span. Figure 1(b) and Figure 1(c) present the generated beam-like properties distributions for the NREL 5 MW blade with the stacking sequence information as defined within the UPWIND project [5]. The extracted values and the fitted LN CDFs are plotted for the tensile modulus $E_x$ of a $[(\pm45/0)_3/(0/\pm45)_3]$ laminate next to the spar cap at the suction side of a cross-section and the sectional bending stiffness in the flapwise direction. They are both calculated at $r=14\text{m}$ distance from the blade root. It is noticeable that the stochastic nature of the material characteristics

![Figure 1. Log-normally distributed properties: (a) $E_1$ tensile elastic modulus parallel to the fibers, (b) $E_x$ effective laminate modulus near the spar cap at the suction side of the cross-section at $r=14\text{m}$ and (c) $E_{lxx}$ flapwise bending stiffness sectional beam property at $r=14\text{m}$.](image_url)
assumed for the individual ply engineering elastic constants (see Figure 1(a)) is also reflected in the integrated properties per laminate and in the overall cross-sectional beam stiffness. This is indicated by the fitted LN distribution function and the approximately 8\% COV of the integrated beam properties that is in line with the 10\% COV of the initial material properties.

In the sequel, certification simulations are performed for both datasets (the stochastic ones - sampled from the LN distributed properties and the reference) and ultimate resultant loads, stresses and deflections are mutually compared.

### 3.2. Aeroelastic Simulations

Time domain aeroelastic certification simulations are performed using the in-house, hydro-servo-aeroelastic solver hGAST [6]. In hGAST, the full wind turbine is considered as a multi-component dynamic system having as components the blades, the drive train and the tower. The components are assembled into the full configuration making use of the multibody formulation. The Blade Element Momentum (BEM) model [7] approximates the aerodynamics of the rotor which may take into account mean inflow characteristics such as yaw, shear, veer and inclination as well as turbulent fluctuations. Viscous effects, unsteady airfoil aerodynamics and dynamic stall are taken into account using the ONERA model [8]. The equations are integrated in time by means of the Newmark 2nd order scheme [9] while the output consists of time series of internal loads and deformations on the FEM grid of the wind turbine components. The simulations are performed under turbulent wind inflow conditions specified within a box of “turbulent wind velocity data”. The defining parameters for the turbulent wind simulations are also specified in accordance with the IEC standard [1].

### 3.3. Statistical extrapolation process

A numerical tool implementing the procedure for estimating the design values of loads, deflections or stresses, based on the IEC guidelines has been developed in MATLAB. It reads a set of time series (i.e. loads, deformations, stresses) and provides ultimate values. A brief description of the relevant steps and their theoretical basis is provided in the following paragraphs.

The method for extracting peak extreme values time series is the peak over threshold (POT) method. For every 10 min simulation, the POT method outputs all values above a certain threshold. According to the IEC code [1], the threshold is chosen to be 1.4 times the standard deviation above the mean value estimated through all realizations per wind speed bin. Also, a time separation of 10 sec between successive maxima is specified to ensure statistical independence.

Then an analytical distribution function is fitted to the sampled peak data, which estimates the extreme value corresponding to the fifty-year return period through extrapolation in time. In the present work, the three parameter Weibull (3pW) distribution function is considered for fitting and it is given in Table 1, equation (1).

It is assumed that the largest load values occur at separated time intervals and that they are statistically independent. For a given wind speed ‘\(V\)’ and a specific observation time ‘\(T\)’, the probability that the largest load ‘\(F_{\text{ext}}\)’ exceeds a given load \(F\) [1], is given by equation (2). Where \(\bar{F}_{\text{max}}\)

\[
F(x) = 1 - e^{-\left((x-c)/\lambda\right)^k}
\]

\[
\text{Pr}ob\left(F_{\text{ext}} \geq F ; V, T \right) = 1 - \left(F_{\text{max}}(F;V,T)\right)^E(n;V,T) \tag{2}
\]

\[
P(F_{\text{ext}} \geq F;T) = \int_{\bar{F}_{\text{max}}}^{V_{\text{out}}} P(F_{\text{ext}} \geq F;V,T)p(V)dV \tag{3}
\]

\[
P(F_{\text{ext}} < F;T = N) = 1 - \left(P(F_{\text{ext}} \geq F;V,T = 10\text{min})\right)^{36524.6N} \tag{4}
\]

| Distribution/Function | CDF                                                                 |
|-----------------------|---------------------------------------------------------------------|
| 3 parameter Weibull distribution (3pW) | \(F(x) = 1 - e^{-\left((x-c)/\lambda\right)^k}\) |
| Short term CDF        | \(\text{Pr}ob\left(F_{\text{ext}} \geq F ; V, T \right) = 1 - \left(F_{\text{max}}(F;V,T)\right)^E(n;V,T)\) |
| Long term CDF         | \(P(F_{\text{ext}} \geq F;T) = \int_{\bar{F}_{\text{max}}}^{V_{\text{out}}} P(F_{\text{ext}} \geq F;V,T)p(V)dV\) |
| Extreme value distribution CDF | \(P(F_{\text{ext}} < F;T = N) = 1 - \left(P(F_{\text{ext}} \geq F;V,T = 10\text{min})\right)^{36524.6N}\) |

Table 1. Short and long-term IEC fitting.
(F; V)' is the short term probability distribution function of the local maxima for the load process, while exponent ‘E(n; V, T)’ is the expected number of local maxima in the observation time period ‘T’ for the mean wind speed bin ‘V’.

Next, the long-term exceedance distribution is applied in estimating the long-term exceedance probability of the extreme value, in reference to a T=10 min period, through partial (short-term exceedance probability) distributions over all operating conditions (wind speed bins) by means of equation (3). As for the extreme value distribution in a specific reference period of N years (i.e. N=50 in the standards), it is derived by assuming independent 10-min intervals and defined in [1] by means of equation (4).

As mentioned in 3.1, simulations are performed for the reference blade structural data (mean values of the properties of the OptiDAT database) and for stochastic data selected from the OptiDAT database (following LN distribution). For the different datasets of structural properties 10 min servo-aero-elastic simulations are performed under normal turbulence conditions (IEC DLC1.1) for 8 wind speed bins with central mean velocities 4, 8, 10, 12, 14, 17, 21 and 25 m/s. For every wind speed bin, 96 turbulent wind datasets are generated (96 wind seeds). A first set of 8(wind bins)x96(wind seeds)=768 servo-aero-elastic simulations of DLC 1.1 are performed for the reference blade structural data. Then, a second set of 768 servo-aero-elastic simulations (for the same wind seeds) are performed using 96 randomly selected blade structural data from the OptiDAT database (fitted LN distributions). The same 96 blade datasets are considered in the simulations of all 8 wind speed bins. Results of the above analyses are presented in section 4.1.

In order to better assess the differences in loads and deflections caused by the uncertainty in the material properties, an additional set of simulations is defined and processed. Twenty different sets of material properties, defining 20 different blade datasets, are randomly selected from the OptiDAT database (fitted LN distributions). For each one of them 24 DLC1.1 servo-aero-elastic simulations are performed at the wind speed of 14 m/s (wind speed at which maximum flapwise bending moment occurs) using different turbulence seeds. POT extreme values extraction is applied to each of the 24 simulations per material set and then a 3pW CDF is fitted to the collected extreme values per material set. Finally, extrapolated values at the 1e-4 probability threshold are recorded in all cases. The same procedure is also applied to the reference blade data using the same 24 wind seeds, in order to

Figure 2. Flowchart illustrating the procedure for the estimation of the design loads/deflections/stresses with varying blade material properties.
compare reference against stochastic material properties on the same basis. Results of the above analyses are presented in section 4.2.

Furthermore, in section 4.2 analyses of the cross section stresses is also performed. A cross-sectional analysis tool [10] based on thin lamination theory is adopted for the calculation of the cross-sectional stresses along the blade span. The tool provides the stress distribution and the Tsai-Wu failure criterion, over the cross section, based on an input set of resultant loads applied at a reference point over the section (i.e. ultimate resultant forces and moments estimated through the servo-aero-elastic analysis). The Tsai – Wu failure criterion [11] is based on the theory of material failure for anisotropic composite materials with different strengths in tension and compression. The criterion predicts failure when the failure index reaches 1, as stated in equation (5),

\[ F_i \sigma_i + F_{ij} \sigma_{ij} \leq 1, \quad i, j=1,2,...,6 \]  

where repeated indices indicate summation and \( F_i, F_{ij} \) denote strength tensors of the second and fourth rank respectively that are experimentally determined, while \( \sigma_i \) denote the stress tensor.

Figure 2 shows the flowchart of the procedure followed in the estimation of the design loads, the deflections and the stresses, with varying blade material properties.

4. Results

4.1. Long term design results

In Figure 3 the long-term exceedance probability of the extreme flapwise deflection at the blade tip and the flapwise bending moment at \( r=14 \) m are presented. Figure 3(a) and (c) compare fitted CDFs of deflections and loads for the reference and the stochastic data. The solid lines correspond to the results for the log normally distributed blade properties while the dashed to the reference ones. The flapwise bending moment is marginally affected by the stochastic material properties, while the flapwise deflection is affected more by the uncertainty in the material properties (higher difference in estimated extreme values between reference and stochastic data). Blade tip deflections exhibit differences higher than 4% with the reference set being more conservative.

Figure 3(b) demonstrates the quality of the fitting of the 3pW distribution to the actual calculated peak load data. The selected extremes exhibit a rather smooth behaviour at high cumulative probability values, while they are less smooth towards the tail of the distribution. This behaviour of the low probability extremes is usually related to high wind speed conditions, in which turbulent content is high and therefore small variations for example in wind direction or pitch angle can result in high variations in loads. This is expected for the flapwise bending moment as its variations are directly associated to variations of the wind.

![Figure 3](image-url)
4.2. Short term fitting design values

The short-term effect of the uncertainty of the material properties on the blade tip deflections, the flapwise moment (at the station \(r=14\text{m}\)) and the stresses are assessed in the present section. The fitted CDF curves for the flapwise deflection and bending moment with stochastic material properties are shown in Figure 4 and compared to the CDF curve obtained for the reference blade properties. By following the procedures of IEC, the predicted expected value of the extreme deflection for the reference and stochastic material properties will be substantially different. On the contrary, the CDF curves for the maximum flapwise moments show much smaller variations. Specifically, the COV of the forecast for the 1e-4 exceedance probability for the blade tip flapwise deflection is 7.7\% and of the flapwise moment at \(r=14\text{m}\) is 0.6\%.

Next, stresses distributions and values of the Tsai Wu failure criterion are calculated over different cross sections along the span of the blade. Calculation of stresses is based on an in-house 2D cross sectional tool, which employs thin lamination theory. Input to the tool is the set of three resultant forces and moments per cross section. In the analyses of stresses, the input set of resultant loads that provide the design stress values of the section, includes the global maximum of the flapwise bending moment per 10min simulation and per cross section of the blade along with the concurrent forces and moments in all other directions.

Figure 5 presents the results of the stress analyses for the reference blade at the cross-section at \(r=22\text{m}\). As demonstrated in the following, this is the station at which maximum stresses are obtained. Figure 5(a), illustrates the mean line along the skin of the section. Extreme values of stresses are recorded at nodes No95 and No100, which are both close to the spar cup on the suction side of the blade (indicated by the two arrows in Figure 5(a)). In Figure 5(b) and (c) the normal (to the cross section plane) and shear stresses (over the cross section plane) along the skin of the section are shown for the different ply sequences. They correspond to six different laminate plies constructed by Triaxial and UD material. The extreme normal stress appears at node No100 and it is equal to 85 MPa. The extreme shear stress is obtained at node No95 and it is equal to -16MPa. For the failure criterion the lowest value is obtained at node No100 (point closer to failure) and it is equal to 2.39 (see Figure 5(d)).

In Figure 6(a), fitted CDFs of the normal stresses of the blades with stochastic material properties at \(r=14\text{m}\) (section where flapwise moments are analyzed) are compared to the CDF of the reference blade. The COV of the extreme (ultimate) normal stress (probability of occurrence of 1e-4) of the blades with stochastic properties is 2\%. In Figure 6(b) the minimum Tsai Wu criterion at \(r=14\text{m}\) is shown for the different wind realizations (24 simulations) and for the different material properties. The

![Figure 4](image_url)  
Figure 4. Short term probability of (a) the flapwise blade tip deformation and (b) the flapwise moment at \(r=14\text{m}\), at wind speed of 14 m/s, for the reference blade data (black continues line) and 20 log normally distributed blade properties (blue dash line).
Figure 5. (a) Mean line of the section skin (b) extreme normal stresses (c) extreme shear stresses (d) Tsai Wu failure criterion at r=22m. Wind speed of 14 m/s.

Figure 6. (a) Short term probability of the extreme normal stresses at r=14m, for the reference blade data (black continues line) and 20 log normally distributed (blue dash lines). (b) Tsai Wu failure criterion values at r=14m, for the reference blade data (circles) and 20 log normally distributed (crosses). Wind speed 14m/s.
The COV of the criterion value for the reference blade (due to the different wind seeds) is 5%. The COV of the criterion value for the blades with stochastic material properties (variation due to different wind seed but also due to different material properties) is 8%. The solid line in the plot corresponds to the mean of the reference blade (criterion value equal to 2.77).

In Figure 7 (a) and (b), the fitted CDF curves for the normal and the shear stresses of the blades with stochastic material properties at r=22m (section where maximum stresses are obtained) are compared to the CDF of the reference blade. The CDF curves for the maximum normal stresses show smaller variation as compared to those of the shear stresses. Specifically, the COV of the shear stresses is 2.5% and of the normal stresses is 1.8%.

In Figure 8, the minimum values of the Tsai Wu failure criterion are shown for the section at r=22m. The COV of the criterion value of the reference blade and the blades with stochastic properties remains 5% and 8% respectively, as in the case of the r=14m station.

In Figure 9(a), the distribution along the blade span of the mean ultimate normal and shear stresses (probability 1e-4) of the different blade sets with stochastic properties are shown. The values of the mean normal stresses range between 68 and 100 MPa, except at the blade root where a significantly lower stress is obtained (25MPa). The root section is cylindrical made of 177 composite laminates which results in lower stress resultants per laminate. The values of the mean extreme shear stresses.
range between 8 and 20 MPa. As already noted, maximum stresses (normal and shear) are obtained at r=22m. In Figure 9(b), the radial distributions of the COV of the mean Tsai Wu value and the extreme normal and shear stresses, due to the material variation are shown. The COV of the criterion lies in the range 7 to 10%. The COV of the extreme stresses is lower, i.e. 2% to 5.5% for the normal and 1% to 3.5% for the shear. It is noted that in the calculation of the Tsai Wu criterion the variation in the yield properties for the different material sets is taken into account and explains the higher values of the COV.

5. Conclusions
In the present work, the effect of the variability of the blade structural properties on the estimation of the extreme loading characteristics is assessed. The simulations indicate that this effect is marginal on the flapwise moments, which are mainly driven by gravitational and aerodynamic loads. The aerodynamic loads mainly depend on the inflow conditions (effective angle of attack and effective velocity).

On the contrary, the blade deflections are significantly affected. The variability of the material properties affects the flapwise deflection of the blade. Long term extreme value analysis of the NREL 5MW blade indicated that higher ultimate flapwise deflection values are obtained for the reference blade data as compared to the stochastically sampled data. The difference in the maximum flapwise deflection is in the order of 8%. This is expected since different material properties lead to changes in the overall blade stiffness properties and therefore different deformations are obtained for the same load.

The stress analysis follows the pattern of ultimate structural loads, but the Tsai Wu criterion, which is directly affected by the material properties, exhibits a similar variability as that of the material properties. The conclusion concerning stress analysis is almost the same for all blade sections. For the levels of the COV of the material properties considered, the extreme stresses and the Tsai Wu criterion COVs are in the order of 2% and 8% respectively.

So in summary, the variability of the blade structural properties primarily affects the blade deflections and the Tsai Wu failure criterion and less the extreme normal and shear stresses. As for the long term flapwise moment forecast, it is even less affected by the material properties.

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