Impact of manufacture-induced blade shape distortion on turbine loads and energy yield

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Abstract. A blade shape distortion develops during the manufacturing process. The distortion is defined as the difference between the target blade shape as per the design and the shape under operational temperatures. This initial distortion varies under operational temperatures due to the different thermal coefficients of expansion of the various blade materials. The resulting manufacture-induced distortion and operational temperatures affect the twist angle, the cross-sectional shape, and the sweep of the blade. Young’s modulus of the blade’s raw materials, i.e., the matrix of the fiber-reinforced polymers and the adhesive material, changes during the manufacturing process, complicating the determination of the distortion. This work calculates the shape distortion for a reference temperature on the basis of a thermal stress analysis using a full 3D finite element blade model. It performs an aero-elastic load simulation for two models: one with the target blade shape and one with the distorted shape. The simulation reveals that the turbine with the distorted shape has an energy yield which is 0.5% lower and a lifetime extension of additional 4.4 years.

1. Introduction

Since the blade designer usually has a finite element (FE) model to hand, this can be used to calculate the thermal blade distortion after cooling of a typical curing cycle during blade manufacture and under operational conditions.

Svanberg et al. validated a model which is based on a thermal analysis including degree of cure [1, 2] with the experimentally obtained shape distortion of a composite C-spar [3]. Nielsen [4] found the modeling approaches, including a cure hardening instantaneous linear elastic (CHILE) approach and a path-dependent approach, for example, to be most favorable for predicting the shape distortion of thick laminates at the root of a commercial wind turbine blade. Baran et al. investigated temperature and cure degree distortion and residual stress development of a pultrusion process of fiber-reinforced polymers (FRP) [5] by way of the example of a pultruded wind turbine blade [6] on the basis of a thermochemical analysis. Ding et al. [7] compared the experimentally determined distortion of a composite C-spar [8] with analytical and numerical models. Moreover, Baran et al. [9] reviewed the mechanical modeling of composite manufacturing processes. Finally, Rosemeier et al. [10] calculated the distortion of a blade and the impact on the development of residual stresses.

This work investigates the impact of the shape distortion on the loads, the energy yield, and the remaining useful life. As the use case, a commercial 1.5 MW IEC class IIA turbine...
located in Northern Germany was investigated, c.f. Rosemeier et al. [11]. An aero-elastic load simulation was conducted for two models: one with the target blade shape and one with the distorted shape. To the authors’ knowledge, no such investigation has so far been presented in the internationally available English language literature.

2. Methods

2.1. Material model

The coefficients of thermal expansion (CTE) of the FRP materials were calculated on the lamina level on the basis of Krimmer’s [12] micro-mechanical Cylinder Fiber Model with hexagonal array (CFM$_h$); c.f. Rosemeier et al. [13]. In order to obtain the CTEs of the FRP materials, the laminates were modeled using classical laminated plate theory (CLT), as described by Reddy [14], for example.

Nickel’s model [15] was adapted by Rosemeier et al. [10] to take into account the thermal expansion of the core material due to the resin uptake of slits in the sandwich core. Resin slits were considered in the longitudinal direction of the blade.

The blade’s raw material properties and the resulting FRP properties can be found in [10], and further details on material experiments in [13].

2.2. Finite element model

A three-dimensional FE shell model implemented in ANSYS APDL was developed to determine the blade distortion. The blade shells were modeled using quadratic shell elements of type SHELL281, while the adhesive layer in the trailing edge was modeled using quadratic solid elements of type SOLID186. Both element types shared coinciding nodes. The FE blade model was constrained at four nodes at the root.

The blade parametrization and input generation were conducted using workflows from the FUSED-Wind framework [16] and the APDL toolbox FEPROC (Finite Element PROCedures) [17] for the meshing, analysis, and post-processing of finite element models.

The FE model consisted of 28,315 shell and 8,800 solid elements.

Figure 1. Finite element model showing extruded shell elements of the trailing-edge cell of the blade (a), and zoom into the trailing-edge bond line modeled with solid elements (b).

2.3. Thermal stress analysis

The FE model was subjected to a thermal load stemming from the temperature difference $\Delta T = T_c - T_o$. The curing temperature of the blade was assumed to be $T_c = 70^\circ$C. The operating temperature was selected to be $T_o = 23^\circ$C. This is the standard class 1 room temperature [18] at which the material properties were determined, i.e., Young’s modulus of the blade’s raw materials.

The average displacement of the cross-section nodes was used to determine the blade distortion, i.e., pre-bend, sweep, and twist. The flat-wise displacement of each node within the cross-sectional plane was used to calculate the distorted airfoil shape.
2.4. **BEM simulation**
Rfoil, an extension of Xfoil [19] which includes rotational effects [20], calculated the polars of 11 target and distorted cross-sections along the blade span. A constant Reynolds number of $4 \times 10^6$ was assumed. The blade element momentum (BEM) theory-based rotor evaluator CCBlade [21] provided the aerodynamic forces and $c_p$-$\lambda$ curves as a function of the pitch angle $\theta_p$.

2.5. **Load simulation**
The use case turbine was modeled in the multibody dynamics simulation software MSC ADAMS (Automated Dynamic Analysis of Mechanical Systems) [22]. The models of the tower and the rotor blades were created using an FE pre-processor.

The Beam Cross-Section Analysis Software (BECAS) [23] calculated the beam properties, i.e., cross-section stiffnesses, masses, shear center, elastic center (centroid), and center of gravity, from the 3D blade geometry and layout provided by SSP Technology A/S [24]. From the detailed FE model, modal bodies for use in ADAMS were derived using constraint and fixed boundary modes in conjunction with the Craig-Bampton method [25]. A total of 24 modes, including rigid body modes, were included in the ADAMS blade model as degrees of freedom. AeroDyn [26] calculated the aerodynamic loads taking into account the aero-elastic coupling with the modal bodies. TurbSim [27] generated the turbulent wind fields. An aerodynamic imbalance of $\theta_p = \pm 0.3^\circ$ as recommended in the design standard DNVGL-ST-0347 [28] was applied as a pitch offset to the blades. It should be noted that this pitch offset was applied in addition to the local twist deviations resulting from shape distortions of the blades.

As the load case for the fatigue limit state, design load case (DLC) 1.2 according to IEC [29] was considered. For the ultimate limit state DLC 1.3, 1.4, 1.5, 2.3, 4.2, 6.1, and 6.2 were considered. The load simulations were conducted for the target blade shape and the distorted shape. The two simulations used the same random seeds in the wind field generation in order to provide comparability between the load sets.

To assess the ultimate limit state, load envelopes were compiled from the ultimate loads of the rotor shaft, the tower top, the tower bottom, and the blade. The envelopes of the blades were obtained for each cross-section along the blade. Then, the envelope was taken from all three blades.

For the fatigue load assessment, the load histories were rainflow-counted [30] to obtain Markov matrices. The damage-equivalent loads (DELs) [31] were then calculated using

$$M_{eq}^i = \left(\frac{\sum_i (n_i \cdot (M_{i}^m))^m}{N_{eq}}\right)^\frac{1}{m},$$

where $M_{eq}^i$ denotes the moment amplitude of the $i^{th}$ load collective, $m$ the negative inverse S-N curve exponent, and $N_{eq}$ the number of equivalent cycles to failure. For the steel components $m = 4$ was assumed, and $m = 10$ for the blade. A reference number of load cycles of $N_{eq} = 10^7$ was used. The DEL per wind speed was weighted according to the probability density distribution (Fig. 5a) of the design site, i.e., IEC [29] class II.

A lifetime extension scenario compared the remaining useful life of the use case turbine equipped with target blades under design conditions with the turbine equipped with distorted blades under the actual wind conditions at the site in Northern Germany. The methodology is described in [11].

3. **Results**
3.1. **Blade distortion and polars**
The FE blade model distorted globally in such a way that the tip swept by 78 mm (Fig. 2a) and twisted by $\approx -0.2^\circ$ (Fig. 2b).
Fig. 2c shows the local distortion of a cross-section at 70% blade span. For better interpretation of the local distortion, the distorted shape was shifted into the lower corner node at the trailing-edge of the target shape.

The lift-to-drag ratio of the polars calculated with the distorted airfoils decreases more in the inboard sections than in the outboard sections (Fig. 2d). The greatest impact is observed at stall angles of attack between 4° and 5°.

**Figure 2.** Global sweep and pre-bent distortion of the blade (a); twist distortion (b); local distortion of the cross-section at \( z = 0.7 \) (c); lift-to-drag ratio of polars determined for target and distorted cross-section at \( z = 0.7 \) (d).

### 3.2. Loads

The loads presented in this section are given in the coordinate system according to the GL guideline [32].

First, the ultimate load envelopes of the target blade shape and the distorted blade were investigated. In the inboard blade region, the in-cross-sectional-plane bending moment \( M_{xy} \) on the distorted blade is smaller than the moment on the target blade (Fig. 3a). The smallest reduction in ultimate bending moment on the distorted blade equals 2.9% and is seen at the blade root (Fig. 4a). In the outboard blade region, however, the bending moments increase on the distorted blade and exceed loads on the target blade. Toward the tip of the blade, the
increase in loads on the distorted blade becomes very large because the load level is small in absolute terms.

The torsional moment $M_z$ along the blade increases due to the blade sweep induced by the distortion. The maximum increase of 75% is found at the root.

![Figure 3. In-cross-sectional-plane bending moment (a) and torsional moment (b) along the blade span.](image)

Furthermore, the effect of the distorted blade on the tower top and bottom as well as on the rotor shaft of the turbine was investigated (Fig. 4a). For the rotor shaft, the in-rotor-plane bending moment $M_{yz}$ decreases by 4.3% and is similar to the difference in blade root loads. As the bending moments on the tower top and tower bottom also depend on the rotor azimuth position, the difference in tower loads does not coincide with the difference in rotor loads.

The fatigue loads on the turbine components were assessed by comparing the DELs of the turbines with the target blade shape and the distorted blade shape (Fig. 4b). The flap-wise and lead-lag DELs at the distorted blade root are up to 1.7% lower than on the target blade root. For the torsional moment along the blade span, a reduction of up to 3.0% is observed. The damage-equivalent bending moments acting on the rotor shaft are reduced by 3.0% as well. For loads acting on the tower, the effect of the load reduction is larger. The pitching moment $M_y$ is reduced by up to 5.0% and the rolling moment $M_x$ is reduced by up to 7.0%.

![Figure 4. Ultimate loads (a) and damage-equivalent loads (b) for selected turbine components.](image)
3.3. Energy yield

The rotor aerodynamics of the turbine with distorted blades are expected to differ from the target specifications because of differences in airfoil characteristics and local twist angles. The effect on the energy yield was assessed by investigating the dynamic power curve and assuming design wind conditions.

Figure 5a illustrates the effect of the shape distortion of the blade. For wind speeds up to $10 \text{ m s}^{-1}$, the power curve for the distorted blade shows that the power output is 0.6% lower on average. A larger deviation from the specified power curve can be seen at wind speeds ranging from $10 \text{ m s}^{-1}$ to $13 \text{ m s}^{-1}$. In these wind speed bins, the power output of the turbine with distorted blades is up to 1.44% lower than that of the target turbine. The energy yield is calculated using the absolute frequency for each wind speed. The total energy yield of the turbine with distorted blades is 0.47% lower than the yield from the target turbine.

![Figure 5. Power curve, energy yield, and wind frequency (a); $c_p$-$\lambda$ curve for target, distorted, and distorted rotor with pitch offset (b).](image)

3.4. Power coefficient

The average deviation of local twist angle is about $0.1^\circ$ (Fig. 2b). The local twist deviations do not differ significantly from the average deviation. Hence, we evaluated whether a correction of the pitch angle can be used to rectify the $c_p$-$\lambda$ curve of the rotor with distorted blades to reduce the losses in energy yield. CCBlade determined an optimum pitch offset angle of $\theta_p = 0.3^\circ$ for the distorted blade. The $c_p$-$\lambda$ curve was calculated for a rotor with the distorted blade and for a rotor with the undistorted blade with a constant pitch offset of $0.3^\circ$. As shown in Fig. 5b, the pitch offset increases the maximum $c_p$ only by a small margin of 0.07%. There is also a small decrease in optimum tip speed ratio $\lambda_{\text{opt}}$ for the rotor with the distorted blade compared with the target rotor.

3.5. Remaining useful life

In [11] we have already shown that the use case turbine situated in Northern Germany would have a remaining useful life of an additional 8.8 years when the actual wind condition at the site is considered rather than the design condition. When the blade distortion is additionally taken into account, the remaining useful life increases to 13.2 years. The rotor shaft remains the critical turbine component.
4. Discussion
This work quantified the distortion of a blade shape. It was observed that the blade twisted by up to $-0.2^\circ$ and the tip swept by up to 78 mm after demolding and cooling. This indicates that the structure of the trailing-edge panel shrank more in the direction of the blade length than did the structure of the leading-edge panel. Moreover, the suction-side and the pressure-side shrank differently. As a consequence, the blade twisted toward feather.

The distortion of the blade, i.e., the blade twist deviation, cross-sectional shape deviation, and blade sweep, could affect the aerodynamic performance of the rotor. Since the turbine controller is generally designed for the target blade shape, the power curve, and thus the annual energy production, might be affected. Although an aerodynamic imbalance of the rotor is considered in the turbine design, i.e., by a pitch angle offset of $\pm 0.3^\circ$ [28], an additional twist deviation of $-0.2^\circ$ can affect the loads on the turbine. The sweep and twist stemming from the distortion should be added to the blade’s pre-twist, which is obtained at rated turbine conditions, and generally considered during the blade design.

The distorted blade leads to generally lower loads of the order of 5% maximum on both the blade and the entire turbine, both in terms of ultimate and fatigue loads. Since the load extrema are generally not applied directly in the design analysis of a component, but rather mean values of the extrema [29], the observed differences in ultimate loads can be neglected. The design of structural components in the machine, and of the tower and foundation, could however directly benefit from the lower fatigue loads.

The decrease in the fatigue loads on the turbine components has a notable effect on lifetime extension. A decrease in DELs increases the remaining useful life of the turbine by 4.4 years when comparing the assessment with the target blade and with the distorted blade.

The benign effect of the decreased loads is, however, offset by the impairment of rotor performance, leading to losses in energy yield of about 0.5% under design conditions. As the average deviation between the power outputs of the target rotor and the rotor with distorted blades is at the same level across the partial power regime, this observation is expected to be made when other site conditions are considered as well. The sensitivity of the blades to turbulence, which has not been investigated in this work, may lead to different results, however. Simple approaches to rectifying the power curve, e.g., by changing the global blade pitch or adapting the generator controller setpoint to the new $\lambda_{\text{opt}}$, are not expected to bring significant improvement to the turbine performance.

As the change in maximum $c_p$ is small, it is not expected that rectifying the generator controller setpoint to the changed $\lambda_{\text{opt}}$ will lead to higher energy yields for the rotor with distorted blades. Hence, the airfoil characteristics are primarily responsible for the deviations in the power curves, and the fact that a pitch angle offset is not a viable option to rectify the rotor characteristics.

The blade distortion shown in this work was calculated at 23°C using a linear thermal stress analysis with $\Delta T = 47^\circ$. Antoniou et al. [33] showed that the residual stress develops linearly along the operating temperature range when a temperature-dependent material model was used. Assuming that the blade distortion behaves similarly to the residual stress and thus can be extrapolated linearly, the twist at a temperature of $-24^\circ$C can be doubled to a twist of $-0.36^\circ$ at the blade tip, for example. Hence, the loads and energy yield decrease further toward lower operating temperatures when the air properties are kept constant.

A future work will investigate the impact of the operating-temperature-dependent blade distortion and air properties on the polars and the rotor loads under the target pitch program. The energy yield and the remaining useful life will be assessed by taking the temperature distribution at the site into account.
5. Conclusions
If the blade shape distortion is considered on the basis of the material properties determined at standard class 1 room temperature of 23°C, the fatigue loads on the turbine components decrease by up to 7% at the tower bottom (Fig. 4b) when comparing the distorted with the target shape. The energy loss is about 0.5% when the controller is not adjusted. Under the conditions assumed in this work, adjusting the pitch controller by adding a pitch offset produced no significant improvement in power output. With knowledge of blade distortions, the rectified polars, twist, and sweep can be considered in the turbine design to decrease possible gaps between design assumptions and observations in the field, especially with regard to power performance. Finally, if the decrease in fatigue loads due to the blade distortion is considered in a lifetime extension scenario, the lower loads give the turbine a lifetime extension of an additional 4.4 years.

Supplemental material
The data used for the figures are available at https://doi.org/10.5281/zenodo.3888942 [34].

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