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Blade research and demonstration platform

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Abstract. At DTU Wind Energy, a 12.6 m reference wind turbine rotor blade and the corresponding blade moulds were designed and manufactured. The entire blade design and the related test data will be published according to the FAIR principles. The blade moulds are intended to serve as a blade research and demonstration platform, allowing to realise theoretical concepts and testing these in full-scale on a wind turbine blade and thus enabling a comparison to numerical solutions. In this article, the preliminary blade design progress and process, initial load calculations and a 3D scan of the blade molds are presented.

1. Introduction
In order to design the blade of tomorrow, researchers and engineers continuously break new ground by developing new methods, concepts and approaches to exceed existing limits and overcome current challenges. To transform innovations from the idea to practical applications in full-scale on modern wind turbine blades, often a lot of simulations, tests and demonstrations of the concepts have to be passed through, whether it deals with advanced aerodynamic, aeroelastic and/or structural design, improved material and manufacturing systems or embedded sensors for future prognostics health management systems to build up a digital twin of the blade.

Currently, there are a few reference wind turbines systems and wind turbine blades concepts publicly available, as e.g. the NREL 5 MW reference wind turbine (1) or the DTU 10 MW reference wind turbine (2). The reference wind turbines concepts allow to verify simulation capabilities through model-to-model comparison and serve as a kind of benchmark concepts. However, the existing reference wind turbine concepts are virtual wind turbines without measurement data to compare with. Existing public available concepts usually focus on detailed aerodynamic and aeroelastic studies, where the theoretical performance and structural response of the wind turbine is investigated. The structural description of reference wind turbine blades is often reduced to stiffness matrix inputs as in (1) or a rough description of the layup as in (2). Moreover, structural details as e.g. adhesive joints in the leading edge, trailing edge or shear web/cap regions are often neglected. The absence of detailed structural definitions leads to individual interpretation of the design and makes benchmarks studies of structural models difficult as seen in ”Results of the benchmark for blade structural models” (3). However, the reference turbines concepts lack not only detailed structural definitions but also test data from experiments/field measurements to compare and thus to validate simulation results in order to quantify the prediction accuracy of numerical tools.
DTU Wind Energy is to not only aiming on closing the gap between simulations and experimental data to compare and validate numerical tools with measurements but also establishing a loop between the design, the manufacturing, testing and monitoring the blade response to create the wind turbine blades of tomorrow. In the following, the preliminary blade design process for the continuously progressing design stage is presented as well as the results of the initial load calculations and a 3D scan of the blade molds.

2. Objectives
The objective of the presented research activity is to create a reference wind turbine blade and the necessary infrastructure to manufacture the blade under controlled conditions. Subsequently, scanning of the blade and non-destructive testing (NDT) will be performed to quantify geometry imperfections and manufacturing flaws. Then, an entire test campaign consisting of static tests, fatigue tests, post-fatigue static tests as well as a modal testing is planned to characterize the blade response. Finally, the entire blade design covering the aerodynamics, aeroelasticity and structural design as well as related test data will be published, allowing to serve as a benchmark. All data describing the blade dimensions and characteristics will soon be published according to the FAIR principles, which means that the data are findable, accessible, interoperable and reusable. Field measurements on an operating wind turbine are planned in the future, in order to validate power curves etc.

In this article, the blade design, initial load calculations and a 3D scan of the blade molds are presented.

3. Methodology
3.1. Blade design
DTU Wind Energy has developed a 12.6 m wind turbine rotor blade. The design process builds up on several iterations between aerodynamic design, aeroelastic design and structural design. The aerostructural design is based on the simulation outcome of HAWTOpt2 (4), which uses BECAS (5), HAWCStab2 (6) and HAWC2 (7), interfaced to a numerical optimizer, resulting in a detailed aerostructural design with lofted shape and internal structural layout. This design is then verified in 3D finite element modelling (FEM) software MSC MARC (8) and ABAQUS (9), and a detailed root design was made, as well as adjustments due to characteristics not accounted for in HAWTOpt2 such as buckling and other nonlinear effects. The blade is designed as replacement alternative for older 150 kW turbines, and as such, one important design requirement is that the blade can be operated as pitch-controlled as well as as stall-regulated blade. Therefore, the blade design does not represent state-of-the-art for modern pitch-regulated blades, but will be unique due to the complete availability of data and measured characteristics.

3.2. Aerostructural design
The preliminary aerostructural design was made using HAWTOpt2, in which we use BECAS to compute the blade elastic properties, combined with HAWCStab2 to compute the steady state aeroelastic response of the turbine, and finally. Optimizing for maximizing annual energy production (AEP) subject to loads, deflection and mass constraints, we arrive at a balanced design, which can subsequently be evaluated further in full-time domain aeroelastic simulations, as well as more detailed 3D finite element models for detailed design. Since the blade should be able to replace older stall regulated blades, the blade is designed only for stall regulation. However, the intention is also to operate it on pitch regulated machines. Future work will also cover the blade operating as a pitch-controlled rotor, and compare its performance with the stall controlled mode of operation.
3.3. Aeroelastic design evaluation

The aeroelastic and non-linear time domain simulation tool HAWC2, is used to compute the loads and fatigue of the blade subject to the full coupled aeroelastic model.

Both the aerodynamic and structural blade design are already adequately described as required by HAWC2, since HAWCStab2 shares the same format and has been used for the aerostructural design. The fully populated matrix has been used as input format to define the structural blade characteristics. The blades are then used to build the full rotor and the 3 bladed regulated wind turbine. In the current implementation, the rotor is mounted at the top of a 24 m tower with a circular cross section for which the outer diameter varies from 2.12 m at the bottom to 0.82 m at the top, and for which 12 mm thick steel is used. A 150 KW generator with a synchronous speed of 1500 rpm and a nominal slip of 0.02, has been used in the model and is implemented in HAWC2 as an external DLL. It should be noted that although representative, the used turbine platform and controller is academic at this point in the design process. In a later stage of the design process a more detailed description, matching a real platform, will be used instead.

An aeroelastic stability analysis is performed in order to evaluate the system frequencies and damping for all wind speeds. After that, load cases DLC1.2 and DLC1.3 from the IEC 61400-1 standards (10) and which are interpreted as outlined in (11), are simulated in order to evaluate representative fatigue and ultimate loads on the blade. The cases are briefly described in Table 1. At a later stage in the project, and once more detailed description of a specific turbine platform is available, the complete set of load cases form the IEC standard will be considered for the load evaluation.

Those loads are then inputs used to evaluate and iterate over the structural design.

### Table 1. Design load cases description.

<table>
<thead>
<tr>
<th>Design Load Case</th>
<th>Design situation</th>
<th>Type of analysis</th>
<th>Wind condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>Operation</td>
<td>Fatigue</td>
<td>Normal turbulence model</td>
</tr>
<tr>
<td>1.3</td>
<td>Operation</td>
<td>Ultimate strength</td>
<td>Extreme turbulence model</td>
</tr>
</tbody>
</table>

The turbine has been designed as per wind class IA from IEC 61400-1 (10). Hence, the average wind speed, the reference wind speed, and the reference wind turbulence intensity used are 10 m/s, 50 m/s and 0.16 respectively.

Six turbulence seeds have been considered for each wind speed, together with three different yaw miss-alignments consisting of 0, 10 and -10 degrees. The effective duration of each simulation is 600 s after discarding the first 100 seconds to avoid initial transients affecting the results.

3.4. Structural design

The structural blade model, DTU’s in-house software Blade Modeling Tool (BMT) was used to generate a 3D layered solid FEM for the commercial finite element package pre/post-processing software MSC Patran (12). The blade structure was discretized based on 20-node layered continuum solid elements, which requires a volume representation of the geometry. The entire blade geometry was modelled based on input data of 99 blade cross sections generated by DTU Wind HawtOpt2 optimization toolchain. These cross sections describe the outer geometry (airfoil) of the blade. Additionally to outer geometry, cross-sections curves were offset according to the layup definition in order to represent the thickness of the laminates. Finally, the individual
cross-sections were connected by spline curves and interpolation surfaces to obtain a volume representation of the blade. The process described in the previous paragraph was handled automatically by the BMT, which utilizes 60 regions/solids to discretize the different cross sectional properties determined by the HawtOpt2 optimization toolchain. Depending on the region, the composite layup consists of 6 to 54 plies through the thickness, where the material properties, layup and ply orientations were assigned to layered 20-node continuum elements. Some redistribution of materials have been made manually in order to get a more homogeneous failure index distribution, to reduce the blade mass and to stay within tower clearance tolerance. Figure 1 depicts a segment of the blade model.

The MSC Marc general-purpose, nonlinear finite element analysis solution solver was used to perform geometric nonlinear analyses.

3.5. BladeLab and blade mould

DTU Wind Energy’s BladeLab provides the entire infrastructure to manufacture the rotor blade, which is made of Saertex unidirectional (UD) U-E-1182 and biaxial (BIAX) X-E-778 fiberglass fabrics infused with Hexion epoxy resin and components glued with Hexion adhesives. A resin mixing and injection system from Bodotex is used to prepare the 2-component Hexion resin (EPIKOTE Resin MGS RIMR 035C & EPIKURE Curing Agent MGS RIMH 037) for infusion. The machine allows to inject resin via a piston in controlled quantities into the laminate.

The moulds are made of glass fibre epoxy with a high temperature epoxy tooling gelcoat used as a surface coat to achieve a strong, temperature-stable mould allowing a maximum service temperature of up to 125°. Moreover, each of the moulds (pressure side and suction side) is equipped with a redundant grid mesh (13) consisting of 110 resistance temperature detectors (RTDs), measuring temperature in the mould, only separated by the gelcoat and two layers of BIAx fabrics from the blade laminate. In order to control the curing process and thus the temperature in the mould on the tool side, an internal heating system based on six different heating zones for each of the moulds is designed. Heating blankets are used to control the temperature from the vacuum foil side.

![Figure 1. Depiction of the blade model segments as defined in MSC Patran.](image-url)
High resolution and precise three-dimensional scans of the blade moulds were conducted, where ATOS III Triple Scan (14) with 8 MP cameras with a 560 mm measuring volume was applied as well as a TRITOP photogrammetry (15) system in combination with ATOS to perform fast and accurate 3D coordinate measurements (Fig. 2). GOM Inspect Professional software (16) was used for the evaluation the data results.

4. Results

4.1. Aerostructural design

The overall properties of the rotor are listed in Table 2.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP (mean_wsp=6.5, k=2) [kWh]</td>
<td>4.486e+05</td>
</tr>
<tr>
<td>Blade length [m]</td>
<td>12.600</td>
</tr>
<tr>
<td>Blade mass [kg]</td>
<td>362.0</td>
</tr>
<tr>
<td>Blade mass moment [kNm]</td>
<td>13.7</td>
</tr>
<tr>
<td>Max rotor speed [rpm]</td>
<td>40.0</td>
</tr>
<tr>
<td>Max Cp [-]</td>
<td>0.474</td>
</tr>
</tbody>
</table>

The structural design features a glass fiber spar cap with a constant width of 0.3 m and two shear webs attached to the spar cap. Figure 4 shows a schematic of the structural layout of the blade. To ensure better alignment of the load carrying structure for the inner part of the blade (close to the root), the spar caps in this region were shifted slightly towards the leading edge. Figure 5 shows the material layup of the shell, spar cap and shear web, where the axis of abscissas represents the normalized blade length from the root to the blade tip. The axis of ordinates shows the material thickness in mm. Note that the plotted layups are the final design layup, described in more detail in Section 4.3. The visualisation of used material and material thicknesses along the blade length are presented in Figure 5 that the shear web thickness stays almost constant, whereas there are significant tapering and changes in the material composition in the spar cap and shell regions.
4.2. Aeroelastic design evaluation

Figure 7 shows the statistics and the short term equivalent fatigue loads of the stall turbine, for the blade root flapwise and edgewise bending moment, and the fore-aft tower bottom bending moment. As it can be seen, the maximum flapwise bending moment achieved is below 150 kNm. The mean edgewise bending moment starts at zero and increases slightly with wind speed, achieving a maximum below 60 kNm and a minimum below -30 kNm. The blade root torsional moment is not critical for this design, hence the tower bottom fore-aft bending moment is illustrated instead, in the bottom-left corner of Figure 7. The blade root loads appear to be higher than the values obtained during the aerodynamic design. Nevertheless, further work need to be done including the study of the tower frequency interaction and the operational points, to better estimate the loads and go through the iterative structural design process.

From the 1 Hz short term design equivalent loads shown in the right column of Figure 7, it can be observed that the damage increases almost linearly as function of wind speed, as expected.
There are small differences between the loads for the three yaw miss-alignments. For the Blade root and tower bottom fore-aft moment, the damage is very similar for 0 and 10 degrees miss-alignment, while it higher at -10 degrees. Similar behaviour is observed for Blade root My, with slightly lower damage at 10 degrees. Nevertheless, the lowest equivalent damage at 4 m/s wind, is observed for all loads at zero degrees.
The life time design equivalent load at the blade root, computed for 25 years, $1e7$ cycles and with Wohler slope $m=10$, is 72 kNm for the flapwise bending moment and around 63 kNm for the edgewise direction.

Figure 7. On the left: load statistics for DLC1.3 of the blade root flapwise (Mx) and edgewise (My) bending moments, and the tower bottom fore-aft bending moment (Mx). On the right column: short term 1 Hz fatigue equivalent loads under DLC1.2, for the blade root flap and edge bending moments, and the tower bottom fore-aft bending moment. Three different yaw miss-alignments are evaluated, and shown fatigue results are using a Wohler slope $m=10$ for the blade and $m=4$ for the tower. No safety factor is applied here.

4.3. Structural design

Based on the initial load calculations from the DTU Wind HAWT Opt2 software, preliminary structural analyses were performed to assess the structural response of the blade.

For the blade under pressure towards suction side (PTS) design loading, a maximum blade deflection of 1.77 m was predicted. For the same loading, a maximum failure index according to the Tsai-Wu failure criterion of 0.6 was calculated, assuming critical material properties as specified in Tab. 3 including a partial safety factor of 2.205.
The blade subjected to the initial PTS design loading led to a maximum longitudinal strain of approximately 3300 µε (Fig. 8). The stress and strain analysis led to a preliminary layup as shown in Fig. 9.

The preliminary evaluation of the three-dimensional mould scans show that some parts of the blade mould seem to deviate from mould design. Here, the moulds have to be checked manually and eventually repairs on the moulds have to be performed to correct for some of the deviations. In future structural simulations, the geometrical deviations from the mould will be included as imperfection in the model.

Table 3. Assumed critical material properties of the used UD and BIA X fiberglass epoxy composite materials including a partial safety factor of 2.205. $X_T$ is the material strength in fiber direction/0° under tension, $X_C$ describes the compression strength in x-direction (on-axis), whereas $Y_T$ and $Y_C$ describe the in-plane strength parameters (tension and compression) perpendicular to it. $S$ is defined as the shear strength parameter.

<table>
<thead>
<tr>
<th>Design strength parameters</th>
<th>UD</th>
<th>BIA X</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_T$</td>
<td>360.0 MPa</td>
<td>69.3 MPa</td>
</tr>
<tr>
<td>$X_C$</td>
<td>257.0 MPa</td>
<td>64.9 MPa</td>
</tr>
<tr>
<td>$Y_T$</td>
<td>24.8 MPa</td>
<td>69.3 MPa</td>
</tr>
<tr>
<td>$Y_C$</td>
<td>63.5 MPa</td>
<td>64.9 MPa</td>
</tr>
<tr>
<td>$S$</td>
<td>16.6 MPa</td>
<td>55.9 MPa</td>
</tr>
</tbody>
</table>

Figure 8. Left: 3D FEM simulations results of the rotor blade illustrated with a color code representing the failure index according to the Tsai-Wu failure criterion of the blade subjected to the PTS design load. Right: 3D FEM simulations results of the rotor blade illustrated with a color code representing the longitudinal strain distribution for the blade subjected to the PTS design load.

5. Conclusions
The article presents the preliminary design of the DTU 12.6 m blade and the blade moulds. The outcome of the described design process allows defining the outer aerodynamic shape as well as a preliminary internal structure (layup stacking sequence). With the fixed blade airfoil and a preliminary structural design, the blade moulds could be manufactured. A detailed structural analysis of the wind turbine blade is required before the blade manufacturing process can start.
Figure 9. Stepwise layup sequences of the DTU 12.6 m blade (step 1 to step 27) for UD and BIAx fabrics (including ply drops) as well as for the core material and the root inserts. The diagonal striped patterns represent either BIAx layers (+45° pattern) or core material/root inserts (-45° pattern), whereas UD layers are illustrated by black, horizontal stripped patterns.

Consequently, a comprehensive load analysis of the wind turbine blade is planned as future work. However, the wind turbine loads and thus the structural requirements for the blade are highly depended on the wind class and wind turbine platform and can vary significantly for different systems. Thus, different wind turbine platforms have to be analysed and the layup has to be fine-tuned according to a specific wind turbine system.

6. Acknowledgement
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