DTU’s blade research and demonstration platform

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Abstract. At DTU Wind Energy, a 12.6 m wind turbine rotor blade and the corresponding blade moulds were designed and manufactured to establish a blade research and demonstration platform. The blade research and demonstration platform shall allow manufacturing of a blade or blade segments under controlled conditions, allowing realizing theoretical concepts and testing these in full-scale for materials, manufacturing and design concepts of next generation wind turbines. For this purpose, the entire blade design with detailed airfoil and structural design as well as the manufacturing and test data of the blade will be published. Static tests, fatigue tests, post-fatigue static tests as well as a modal testing of the manufactured rotor blade are planned to characterize the blade response. In this way, the DTU 12.6 m wind turbine rotor blade and the blade moulds can serve as a reference rotor blade to benchmark numerical simulations and to test new materials, designs, manufacturing concepts or embedded sensors for future prognostics health management systems. In this article, results of a 3D scan of the blade moulds are presented as well as description of the water-based heating and cooling system and a resistance temperature detectors (RTD) measuring system.

1. Introduction

Development of new materials or structural concepts for wind turbine rotor blades requires a transformation of the initial idea via prototypes to a final product. Testing new concepts, materials or manufacturing approaches on small scale and comparing the results with reference cases is often desired to demonstrate the potential of an innovations before applying them on full-scale to large wind turbine blades. This approach reduces the time to market by simultaneously minimizing the financial risks.

Especially, for material suppliers or innovators without access to own wind turbine blade manufacturing and reference cases, it can be challenging and costly to test, benchmark and demonstrate new ideas and concepts. Currently, there exist a few public available reference wind turbine systems and wind turbine blade designs, e.g. the NREL 5 MW reference wind turbine [1] or the DTU 10 MW reference wind turbine [2]. However, these reference wind turbine concepts are mainly designed to serve as benchmark concepts for model-to-model comparison with focus on aerodynamic and aeroelastic content. The wind turbine blade structural representation is often reduced to stiffness matrix inputs [1] or only roughly described [2] without documenting structural details as e.g. the design of adhesive joints or ply drops.

At DTU Wind Energy, a blade research and demonstration platform has been designed and built to overcome the shortcomings of the aforementioned reference wind turbine concepts. DTU’s new research and demonstration platform does not only provide detailed aerelastic, aerodynamic and structural calculations of a 12.6 m long wind turbine blade but also material
properties and characteristics according to DTU’s curing cycles process. Moreover, DTU Wind Energy has developed an advanced blade mould, where the entire loop of numerical validation, manufacturing, testing and monitoring of new materials, manufacturing processes or structural concepts can be simulated and tested. With DTU’s Large Scale Facility for structural blade testing testing of the final structural blade response can be investigated too. In the near future, all test data, simulations results as well as the entire blade and mould design will be made publicly available according to the FAIR principles, which means that the data are findable, accessible, interoperable and reusable.

The objective of DTU’s research initiative is to create a blade research and demonstration platform and the necessary infrastructure to manufacture and test a wind turbine blade under controlled conditions to serve as reference wind turbine blade platform, allowing to experiment with new blade technologies and materials to create the wind turbine blades of tomorrow.

Mortensen et al. [3] demonstrated on panel level how curing process cycles and conditions can significantly affect the fatigue performance of unidirectional composite materials. By modifying the curing process, residual stresses in an epoxy-based fiber composite material could be reduced, which significantly improved the fatigue performance of these laminate by a factor of five. However, industry prefers short curing process cycles and conditions to decrease mould time per unit and at the same time to increase the production capacity. This can be achieved through the acceleration, automation and digitization of the entire composite manufacturing process compared with current production methods. Blade manufacturing processes can be improved by high precision handling methods, prefabricated inserts (precasts) and automation, where e.g. the effectiveness of the production methods can be measured by the amount of fibreglass material placed in the mould in a given amount of time (i.e. kg of fibreglass per hour). Combining modelling and real time assistance, monitoring and control of the manufacturing process through laser projection systems, augmented reality and wide range of sensors can help to optimize the manufacturing process and to reduce non-conformance in the final blade structure. Moreover, embedded sensors and heating and cooling systems in blade moulds in combination with data algorithms and control systems can improve the resin infusion process and the temperature profile of resin curing process and thus purposefully affect the residual stresses and manufacturing time. All these aforementioned steps towards faster, cheaper and improved manufacturing processes have in common that they have to be optimized and tested.

DTU Wind Energy’s blade mould has to offer three key features, which make the blade research and demonstration platform to an advanced testing environment. The following three aspects will be discussed more in details in this article.

- Precise scans of the mould geometry to be aware of mould geometrical deviations and imperfections as well as post-casting scans of the shells in the mould for estimation real thicknesses of the shells
- Embedded water-based heating and cooling system to control the curing process
- Dense mesh of digital resistance temperature detectors in the mould for monitoring and controlling processes

2. Methodology

DTU Wind Energy’s has developed a 12.6 m long wind turbine blade. In this article, focus is paid to the wind turbine blade mould, its geometry as well as to the manufacturing process and equipment to monitor and control the blade manufacturing. The design process builds up on several iterations between aerodynamic design, aeroelasticity design and structural design. The design process itself, the applied techniques and methods as well as preliminary results are described in detail in [4].
2.1. Mould heating
The moulds are made of a glass fibre epoxy composition. A high temperature epoxy tooling gelcoat is used as surface coat to achieve a strong, temperature-stable mould. The epoxy tooling gelcoat allows a maximum service temperature of up to 125°C, which makes it possible to use the mould with both polyester and epoxy resins. To be in better control of the temperature in the mould on the tool side, an embedded water-based heating and cooling system has been installed to both the pressure and the suction sides of the blade moulds, which will improve the curing process fine-tune capabilities to adjust the level of residual stresses in the blade laminates. Each of the heating and cooling system consists of six independent water loops connected to a heating/cooling unit with fast-responding valves controlled by in-mould resistance temperature detectors. The maximum water temperature is designed to be around 95°C. The tubes of the heating and cooling system are arranged in such a way that the hot inflow is running parallel to the cool outflow water and thus enabling a more uniform temperature field in each of the heating regions. Heating blankets are used to control the temperature from the vacuum bag side. Initial test of the heating system have been conducted, where ca. 60°C warm water was used to heat up the blade moulds and subsequently each water loop was supplied with it.

2.2. RTM mesh
Both the pressure and the suction side of the blade moulds are equipped with a redundant grid mesh [5], each consisting of 110 resistance temperature detectors (RTD) measuring temperature in the mould. Only the gelcoat and two layers of biaxial fabrics separate the RTD grid mesh from the blade laminate surface. The RTM grid mesh was developed to simultaneously measure cross-sectional temperature and resin flow distribution in the mould. The sensor mesh consists of a set of 110 resistors per mould arranged in a regular grid (see Figure 1b). Platinum temperature Surface Mounted Device (SMD) resistors with a 1206 package dimensions and 1K ohm resistance were soldered to a enamelled 0.5 mm thick copper wire. The cross-sectional measurement concept is based on electrical resistance, where a special multiplexing-excitation scheme is applied with constant voltage. The measurement system approach is based on the work from Martin Arlit et al. [5]. A first prototype of this measurement technique to determine the temperature in the mould had been successfully tested on smaller scale (see Figure 1a).

![Figure 1: RTM test panel (a) and RTM grid mesh placed on the biaxial fabric layer during the wind turbine blade mould building process (b).](image)

2.3. Mould geometry
In order to evaluate imperfections and manufacturing deviations of a produced wind turbine blade, it is important to know the blade mould quality and to localise and quantify mould
deviations. For this purpose, high resolution and precise three-dimensional scans of the pressure side and suction side of blade moulds were performed. Both, an ATOS III Triple Scan with 8 MP cameras and 560 mm measuring volume as well as a TRITOP photogrammetry system was used in order to perform fast and accurate 3D coordinate measurements (Figure 2). The equipment is produced by GOM GmbH, a Zeiss company and distributed by Zebicon a/s (Hedegaardsvej 11, 7190 Billund (Denmark) for region Denmark. For this project, Zebicon collaborates with DTU Wind Energy and conducted the mould scans.

The raw data consisting of 50 million measurement points was reduced to a data set with 4.2 million measurement points and post-processed with GOM Inspect Professional software [6] to evaluate the deviations of the manufactured moulds in comparison with the Computer-Aided-Designed 3D model, technical drawings and manufacturing inputs.

In addition to the three-dimensional scans, three cross-section stencils were created for locations around the highest deviations according to the measurements conducted by Zebicon a/s. Stencils at a radial blade position at 4.00 m, 4.40 m and 4.80 m were produced with a laser-cutting process and placed in the pressure side mould to conduct manually measurements. For each of the selected cross-section, both, a cross-section stencil representing the airfoil as designed and another one with a 15 mm offset were produced (Figure 3a and 3b).

Figure 2: Three-dimensional coordinate measurements and scans of the blade moulds (the figure is taken from [4]).

3. Results

3.1. Mould heating

The heating/cooling system allows an individual temperature regulation of the six independent regions. First tests have shown an individual heating of the separated heating/cooling loops works as planned. In the upstart phase, the water pipes on the tool side are clearly visible as shown in Figure 4, where the temperature field was measured with a FLIR A655sc FOV 25° high resolution thermal imaging and measurement camera (640 x 480 pixel microbolometer that detects temperature differences down to <30 mK) from FLIR Systems, Inc. (27700 SW Parkway Avenue, Wilsonville, OR 97070, USA). After approximately 3 min, the water pipe system leads to a much more homogeneous temperature distribution for the specific heat cycle. Figure 4 shows the temperature distribution along the blade mould. On the left hand side a heating loop has been heated up over several minutes and the temperature is more homogeneously distributed, whereas the heating cycle in the blade tip has just been activated and the heating pipes of the loop are clearly visible.
Figure 3: Airfoil cross-section stencils (a) and stencils with 15 mm offset (b) to check the mould quality and to quantify the deviations in specific locations of the wind turbine blade mould.

Figure 4: Temperature distribution (in °C) around the blade tip of the mould measured with a thermal camera and visualized with the FLIR ResearchIR Max software.

3.2. Mould geometry

The 3D scans conducted by Zebicon as well as manual measurement at specific cross section of the mould geometry have shown significant deviations from the mould design as visualised
in Figure 5. In the figure, the best fit of the superposition between the CAD model and the 3D scan leads to a maximum deviation of 13.9 mm detected at a radial position of 4.32 m. The manually measured maximum deviations of approximately 11 mm were measured both, at the blade cross section position at 4.00 m and 4.40 m blade radial position. The distance between the manually measured maximum deviations and 3D scan is approximately 120 mm.

Figure 5: Best fit of 3D scan of the pressure side mould. Deviations in mm are visualized according to the colour code.

Figure 6 shows a cut-out of the blade mould around 4.20 m to 4.40 m radial position of the blade and depicts the 3D scanned mould geometry superimposed with the CAD blade model. The figure shows clearly that the pressure side mould around the trailing edge panel is significantly curved inwards towards the blade center but does it smoothly, so that no abrupt changes/grooves in the blade mould geometry can be seen. The blade mould for the suction side shows also local deviations but the discrepancy is much less pronounced compared to the pressure side mould.

3.3. RTM mesh
The dense RTM mesh grid with 110 sensors per mould has not been tested yet. However, first measurements of the test specimen were conducted successfully and accurate measurement results were acquired. In the near future, the RTM mesh grid will be tested and its performance evaluated.

4. Conclusion
In this article, the 3D scans of the blade moulds are presented as well as the water-based heating and cooling system and a resistance temperature detectors (RTD) measuring system is introduced. The water-based heating and cooling system demonstrated to heat up the blade mould effectively and also to lead to a fairly uniform heat distribution after a short time. However, further investigations have to be conducted to investigate how accurate and time-efficient the water-based heating and cooling system can be applied to tailor the curing process of the composite.
The installed RTD measuring grid has proven to work precise on for the test panel. The RTD mesh grid installed in the blade moulds seems to be promising but has to demonstrate in practice how precise the dense mesh can not only measure the temperature field in the mould but also detect the resin distribution/front during vacuum infusion processes.

The 3D scans of the blade moulds have detected and quantified significant deviations between the CAD model of the moulds and the manufactured blade moulds. The deviations deviate partly significantly from industrial standards, where usually ± 2 mm are the tolerable discrepancy. The deviations will not only affect the manufacturing process, where e.g. the shear web geometry has to be adapted, but also the blade structure and possibly the aerodynamic response too. However, to quantify the effect of the structural deviations/imperfections on the structural and aerodynamic response, numerical simulations have to be performed and analysed in order to evaluate and quantify how critical the significant deviations are for the structural integrity of the blade and its aerodynamic performance are. Moreover, the fitting of the shear webs has to be analysed in case modifications will be required. For this purpose, the high resolution surface scans of the blade moulds will be converted into FEM geometries and numerical simulations will be used to quantify the effect of the geometrical deviations. This deviation will allow to demonstrate one of the concepts within Digital Twin approach where feedback from latter stages should be used to update models of the earlier stages.

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