Highly Efficient Adaptive Fiber-Composite Rotor Blades

Additive Manufacture of FRP Injection Molds for FRP Components of Small Wind Turbines

Currently, small wind turbines can hardly be operated profitably in landlocked regions. This drawback has now been overcome by the partners EAB Gebäudetechnik Luckau GmbH and the Chair of Polymer-based Lightweight Design at the BTU Cottbus-Senftenberg: passive smartblades made from 3D-printed molds adapt independently to wind conditions. This is achieved by an intelligent layer structure and its bending-torsion-coupling.

This newly developed rotor blade is especially suited for weak-wind regions and adapts independently to the wind load © BTU

The share of renewable energy sources is constantly expanding. Cost increases due to this energy transition have been financed since 2000 via the EEG surcharge (EEG: Renewable Energy Sources Act). Approximately one-third of the entire surcharge is born by private households and small companies. This motivates many private individuals to supply themselves proportionally with small wind turbines (SWT). At wind speeds below 12 m/s, the SWTs that are profitable in coastal regions usually do not achieve nominal output. In landlocked areas, sufficient wind speeds are rarely reached.

Average wind speeds in landlocked areas are usually less than 5 m/s at a height of 10 m. In Germany, SWTs up to this height do not require approval, but are not profitable in such areas. The greatest influence on efficiency comes from the rotor blades, most of which have been designed until now for regions with strong-to-medium winds. They are scaled in size by the manufacturers according to similarity.

The Inland Path to Profitable SWTs

For SWTs to pay for themselves for inland private households as well, they have to be designed for regions with weak and middle winds. To this end, the EAB Gebäudetechnik Luckau GmbH and the Chair of Polymer-based Lightweight Design at the BTU (Brandenburg University of Technology) Cottbus-Senftenberg, Germany, have combined and implemented two innovative approaches:

- Geometry optimized for weak-to-middle wind regions and
- independent braking by blades that passively adjust their pitch to the wind load.

Profiles for weak-wind regions were selected and verified using a design and simulation program (QBlade v0.96.3, HFI TU Berlin, Germany). Based on the profiles, a preliminary blade geometry was designed and simulated. The complete rotor blade design was implemented via a CAD program (Rhinoceros 6.0, Robert McNeel & Associates, Seattle, WA/USA) (**Fig. 1**). The design took into account whether the product could be manufactured as a fiber-composite construction.

Efficient Product Development thanks to Modern Simulation Technology

Rotation speed and power are influenced by the pitch of the rotor blades. Passive adjustment of the blade pitch achieved by bending-torsion coupling (BTC) can enable starting at low wind speeds and achieve high yields with high wind loads.

Fiber-reinforced plastics exhibit anisotropic, i.e., direction-dependent materials properties. This anisotropy leads to deformation coupling when the fiber orientation in layer sequences deviates from 0° and 90° as well as when the layup is asymmetrical. For example, given an appropriate fiber orientation, the bending moment can not only cause bending deformation, but twisting as well [1–3].

Using the Finite Element Method (FEM), a layer structure was ascertained that exhibits BTC and withstands loading. As the wind load increases, the blade twists into the wind, thus reducing blade speed to nominal power and rendering it unnecessary to brake the system (**see Infobox p. 11**).

Two loads affect the rotor blade essentially:

- Centrifugal force due to rotation and
- pressure distribution from the wind load.

The complex pressure distributions affecting the rotor are not known in advance and thus have to be calculated.

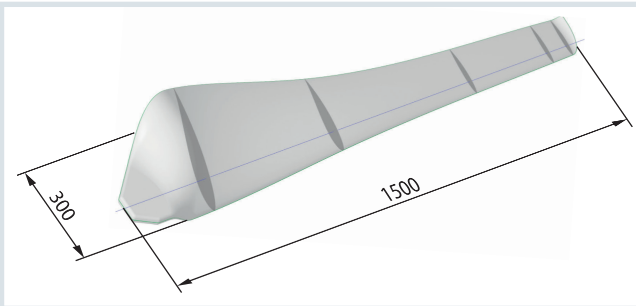

Fig. 1. Production-ready implementation of a rotor blade design with the profiles and the profile chord © BTU

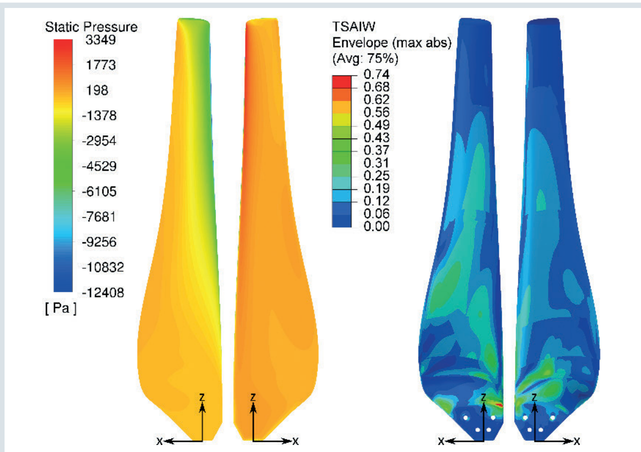

Fig. 2. Distribution of pressure on the rotor blade and Tsai-Wu failure criterion (TSAIW). There is no damage to the laminate at TSAIW < 1 © BTU

CFD and FEM Calculations: Torsion under Wind Load

Following meshing, the further model design, calculation, and evaluation are performed in Ansys Fluent 3D and Ansys CFD-Post (Ansys, Inc., Canonsburg, PA/USA; CFD: Computational Fluid Dynamics). The two-equation model SST k-ω is chosen as the turbulence model. The calculation of the steady-state solution with the pressure-based solver assumes an extreme load case with a wind speed of 20 m/s and a rotation speed of 460 revolutions per minute. The resulting pressure on the rotor blade (**Fig. 2**) is exported in a corresponding FEM data format.

The FEM models are solved using Abaqus from Dassault Systèmes of Vélizy-Villacoublay, France. They consist of several components connected by constraint and contact conditions. In the first calculation step, the bolts that fix the blade to the hub are pretensioned; in the second step, the centrifugal force and pressure load resulting from the wind load are applied.

Using a Python script, the torsion angle is calculated on the basis of the FEM results and used together with the Tsai-Wu failure criterion [4] (**Fig. 2**) for evaluation in the Abaqus CAE software to obtain »

Hybrid manufacturing process			
Phase 1: additive manufacturing		**Phase 2: substractive manufacturing**	
Plastic granulate	AC004XXAR 1 (Sabic)	Milling tool	Ball mill R = 8 mm, 2 cutting edges
Nozzle diameter	6 mm	Speed of rotation	18,500 rpm
Speed	75 mm/s	Milling speed	10 m/min
Layer height	2 mm	Step XY	0.25
Line width	8 mm	Step Z	4 mm, final geometry in one milling sequence
Near-net-shape number of paths	2		
Geometry offset	4 mm		

Table 1. Process parameters in the hybrid production of mold halves Source: BTU, CNC Bárcenas-Bellón

Advantages of the System

Small wind turbines are usually actively braked by a short circuit from the generator to lower the speed of rotation. This newly developed rotor blade brakes itself passively thanks to bending-torsion coupling.

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References & Digital Version

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German Version

- Read the German version of the article in our magazine ***Kunststoffe*** or at ***www.kunststoffe.de*** optimal laminate utilization and a large torsion angle. Evaluation of the layer structure includes consideration of an efficient manufacturing method. The developed blade having an asymmetrical layer structure achieves significant torsion under wind load when compared to a quasi-isotropic standard [0/90/± 45] layup (**Fig. 3.**)

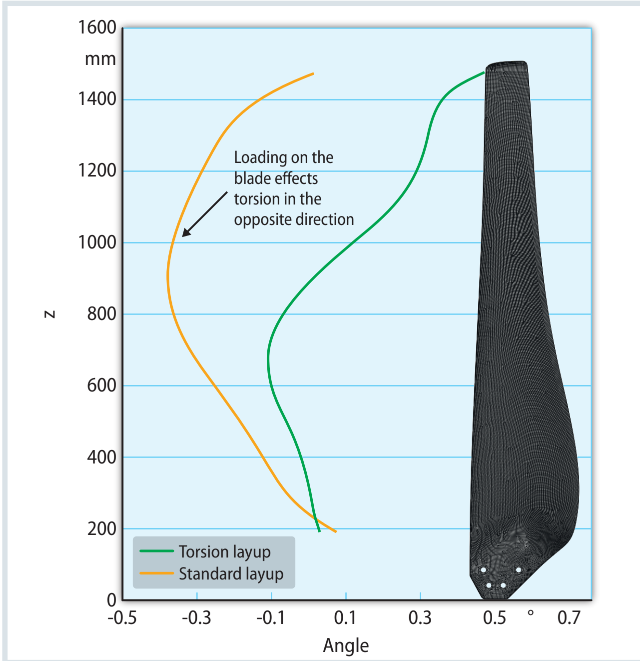

Fig. 3. Regression curves (polynomial, degree 6) of torsion angle over blade length at a wind speed of 20 m/s Source: BTU; graphic: © Hanser

Additive Manufacture of an FRP-Based Mold

A special two-piece mold was developed for the technical implementation of the new generation rotor blade (**Fig. 4a**). For the first time, a direct extrusion system was used that combines both additive and subtractive plastics processing methods in a single system and has been available since March 2021 at the BTU's Institute of Lightweight Design and Value-added Management (ILW).

Additive manufacturing has enormous potential for cutting the time and expense required to manufacture molds for FRP parts. The combination of materials application at high-volume flow (by direct extrusion of thermoplastic polymer granulate) with downstream single-step subtractive fine finishing enables short-order mold construction (direct tooling). For small numbers of moldings this hybrid procedure enables more economical mold manufacture thanks to high materials efficiency and short process times thanks to the high output from the extruder.

Compared to classical mold making, the direct tooling approach has the advantage of considerably reducing the number of manual working steps. Beyond that, it also notably reduces component mass by realizing the large-volume mold (1700 x 500 x 350 mm) as a thin-walled hollow body structure. The printed mold weighs about 30 kg and can be handled by two persons. The mass of a comparable aluminum mold would weigh about 500 kg, depending on the particular design.

Both mold halves were manufactured using the Super Discovery hybrid production cell from its builder, CNC Bárcenas-Bellón S.L., Valdepeñas, Spain. This is a two-step technology consisting of direct extrusion of fiber-reinforced plastic granulate and subsequent milling within a machine. The use of plastic granulate (here an ABS-CF20) enables efficient materials discharge up to 25 kg/h. Direct extrusion also favors near-net-shape materials application. A single fine-finishing is the only reworking required to create a sufficient surface finish in the mold cavity. Roughing is eliminated.

This technology departs here from the classic milling sequence of glued polyurethane or epoxy resin-based block materials which requires roughing in several milling steps and smoothing over several times. Given a suitable choice of parameters (**Table 1**), efficient, materials-saving, near-net-shape 3D printing with a final fine finishing reduces time, materials, and expense as well (**Fig. 4b**). Fillets are already included in the design to keep the mold from swinging open during the subsequent milling sequence.

Manufacturing the Rotor Blades from Fiber-Reinforced Plastic

The fiber-reinforced rotor blades were manufactured by infusing fiberglass layers and fabrics with epoxy resin (**Fig. 4c**). The precise positioning for gluing the GRP shells was performed in the closed mold halves (**Fig. 4d**).

The set of newly developed rotor blades has been scheduled for testing in Luckau, Brandenburg, Germany, starting in May 2021. The resulting data will be recorded over the course of a year and compared with the data from classic designs recorded in 2020. ■

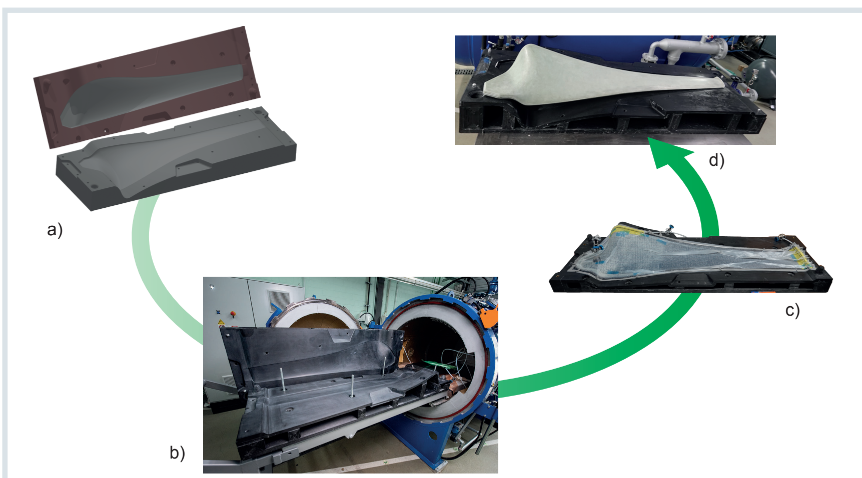

Fig. 4. Development of the mold for manufacturing rotor blades. a) CAD model of the mold; b) printed mold; c) infusion of a rotor blade half; d) rotor blade following gluing of both shell halves Source: BTU; graphic: © Hanser