STRUCTURAL DESIGN AND VALIDATION OF A 10 KW WIND TURBINE BLADE

L.-C. Forcier[1], J. Sumner[2], T. Gagnon[3], J.-F. Charron[1], S. Joncas[1*]
[1] Department of Automated Manufacturing Engineering, École de technologie supérieure, Montréal, Québec, Canada, [2] Physics Department, Dawson College, Westmount, Québec, Canada, [3] Department of Mechanical Engineering, École de technologie supérieure, Montréal, Québec, Canada ,
* Corresponding author (simon.joncas@etsmtl.ca)

Keywords: *Wind turbine blade, composite materials, finite element analysis, structural optimisation.*

Abstract

In this paper, the structural design and validation of blades for a variable pitch and speed 10 kW wind turbine is presented. Blades are 3.76 m long and built using glass/epoxy composite materials. The design of this wind turbine was made according to the IEC 61400-2 standard on small wind turbines. Blade loads were computed using the FAST aeroelasticity software. The blade structural design was made with the OptiStruct finite element solver using the strutural optimisation capabilities of this software in the early stages of the preliminary design. The blade was vacuum infused in three parts (upper skin, lower skin and shear web) and bonded togheter in a subsequent step. Static and modal structural test showed that the blade is able to resist to the design loads and that experimental results are similar to numerical results.

1 Introduction

This paper presents the structural design and validation of a composite blade for a 10 kW wind turbine designed at École de technologie supérieure in Montréal (Québec, Canada). The project was funded by the Natural Sciences and Engineering Research Council of Canada's Wind Energy Strategic Network (NSERC/WESNet). This network was formed to promote wind energy, to find new technical solutions, to help canadian manufacturers to invest the wind turbine industry and to form highly qualified personnel. About 150 students were funded by WESNet during the five year duration of the network. The 10 kW wind turbine project was launched to test new technologies developped by WESNet researchers, demonstrate and evaluate these technologies on a wind turbine and transfert the technology to the canadian industry. The wind turbine was designed and manufactured over a 15 month period, between January 2011 and March 2012. It was commissioned in June 2012 and is now being monitored at the Wind Energy Institute of Canada (WEICan) on Prince Edward Island.

After a short presentation of the 10 kW wind turbine characteristics, the blade aerodynamic design will be outlined. A section will then be dedicated to the blade loads computation. The blade structural design methodology and final design will be presented next. Finally, the blade validations tests will be described and compared to the numerical results.

2 Wind turbine characteristics

This turbine is a pitch regulated variable speed wind turbine equiped with a direct drive synchronous generator designed at University of New Brunswick (Canada). The rotor diameter is 8.08 m and the turbine reaches its nominal electric power of 10 kW at a wind speed of approximately 9 m/s and a rotor speed of 185 rpm. For wind speeds below this value, the blade pitch angle is fixed and the rotor speed is adjusted to get the maximum power output. For winds above the nominal speed, the pitch control system is activated to maintain the rotor speed as close as possible to 185 rpm and consequently limit the power output to 10 kW. No yaw control system is needed as the rotor use a downwind configuration and the nacelle yaw motion is unconstrained. The rotor therefore auto aligns itself when the wind direction changes. Table 1 summarize the wind turbine characteristics and Figures 1 and 2 show respectively the nacelle without its covers and the assembled wind turbine.

3 Blade aerodynamic design

The blade uses airfoils of the Delft University of Technology family [1] and was designed using blade element momentum (BEM) theory. As the aerodynamic design has to consider both aerodynamic and structural considerations, in the early stages of the aerodynamic design, conservative characteristic loads were used to verify that the current design met the structural requirements.

Table 2 shows the final aerodynamic design of the blade. Thicker airfoils are used near the blade root

Table 1: WESNet 10 kW wind turbine characteristics

Nominal power	10 kW
Cut-in wind speed	3 m/s
Nominal wind speed	9.5 m/s
Number of blades	3
Rotor speed range	0–250 rpm
Nominal rotor speed	185 rpm
Rotor orientation	downwind, free yaw
Rotor diameter	8.08 m
Nominal tip speed ratio	8.5
Hub height	24 m
Control system	active pitch
Hub radius	0.28 m
Rotor coning	3°
Generator	variable speed, direct drive

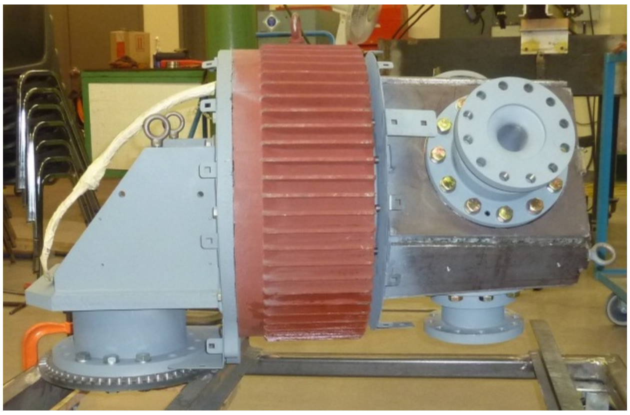


Figure 1: WESNet 10 kW wind turbine nacelle without covers.

Figure 2: WESNet 10 kW wind turbine.

Table 2: Blade aerodynamic shape. r is the distance from blade root, c is the airfoil chord length and θ_T is the airfoil twist angle.

r [m]	θ_T [deg.]	c [m]	Airfoil
0.000	15.3	0.200	Circle
0.160	15.3	0.200	Circle
0.560	15.3	0.334	DU-97-W-300
0.760	14.5	0.318	DU-97-W-300
0.960	13.7	0.303	DU-91-W2-250
1.160	12.9	0.287	DU-91-W2-250
1.360	12.1	0.271	DU-91-W2-250
1.560	11.2	0.256	DU-91-W2-250
1.760	10.4	0.240	trans. 212-250
1.960	9.6	0.224	DU-00-W-212
2.160	8.8	0.208	DU-00-W-212
2.360	8.0	0.193	trans. 180-212
2.560	7.2	0.177	DU-96-W-180
2.810	6.2	0.157	DU-96-W-180
3.060	5.2	0.138	DU-96-W-180
3.260	4.3	0.122	DU-96-W-180
3.460	3.2	0.106	DU-96-W-180
3.660	1.3	0.090	DU-96-W-180
3.760	0.0	0.083	DU-96-W-180

for structural reasons. Sectional loads are higher at this location and thicker airfoils allow a higher section modulus. Near the blade tip, where the sectional loads are lower, it is possible to use thinner airfoils to get maximum aerodynamic efficiency.

4 Blade loads computation

Once the aerodynamic design was fixed, to determine the blade design loads, the turbine was analysed using the aeroelasticity code FAST [2]. This software models the entire wind turbine as an assembly of rigid and flexible bodies. In our analysis, all parts were considered rigid and the only degrees of freedom that were taken into account were the nacelle yaw motion and the variable rotor speed.

As the wind turbine is a free yaw downwind machine, the only control strategies to model were the variable rotor speed and the blade pitch control mechanism. The variable rotor speed control was modeled by specifying the torque / rotational speed curve of the generator as supplied by the designer. The pitch control system use a proportional-integral controler. The control systems was modeled with Simulink using the FAST's Simulink interface.

All the relevant ultimate load cases of the aeroelastic method defined in the International Electrotechnical Commission (IEC) standard on design of small wind turbines [3] were evaluated using FAST. These load cases include normal power production, power production with control system fault, shut down, idling and parked wind turbine for different wind conditions.

The fatigue load cases were treated differently. In addition to the aeroelastic method, the IEC standard presents a simplified method to evaluate conservative load cases. The simplified fatigue load case is based on the load range of a wind turbine that operates between 0.5 and 1.5 times the design rotor speed and 0.5 and 1.5 times the rotor aerodynamic torque. The simplified method also includes the possibility to analyse the fatigue load case as a static load case using a safety factor of 10 on static material strengths. The fatigue load case used is based on this procedure. The nominal operation condition was modeled with FAST to get the aerodynamic loads and the gravitational and inertial loads were applied directly in the finite element model.

This analysis of all load cases with FAST allowed to identify, in addition to the fatigue load case, 3 critical load cases to use for the blade structural design: maximum root axial force, maximum root edgewise bending moment and maximum root flapwise bending moment. The maximum root axial force and edgewise bending moment occur when the wind turbine in normal operation is submitted the the normal turbulence model with a wind speed of 25 m/s. The maximum root bending moment happens when the wind turbine in normal operation faces the extreme operating gust at nominal wind speed. During this situation, wind speed increases suddenly from 9.5 m/s to 14 m/s and then reduce to 9.5 m/s. This causes an acceleration of the rotor speed that causes a rapid nacelle yaw movement generating high out-of-plane gyroscopic forces. These forces are in the opposite direction of the aerodynamics forces so that the blade's upper surface is in tension and the lower surface is in compression.

According to the IEC61400-2 standard, a safety factor of 1.35 was applied to the ultimate loads and no safety factor was applied on fatigue load.

5 Blade structural design methodology

Figure 3 shows a schematic representation of the topology of the blade cross section. The blade is made of three parts (upper and lower surfaces of the airfoil and shear web) bonded together. Both aerodynamic shells are thicker in the maximum thickness region of the airfoil (between 15 % and 45 % of chord length) to form the spar caps that support most of the blade loads.

The materials used in this blade are similar to those of large wind turbines. The main structural material is

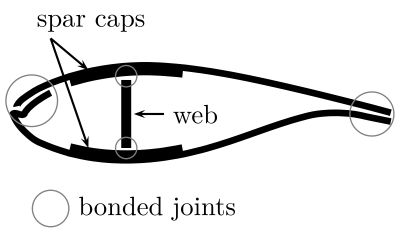


Figure 3: Blade internal structure.

Saertex glass fiber with Gurit's Prime 20 epoxy resin. Two different non crimp fabrics (NCF) are used : a 655 g/m^2 unidirectional fabric for plies at 0° (fiber in the blade longitudinal direction) and a 609 g/m^2 bidiagonal fabric containing plies at +45° and −45°. 0° plies are 0.50 mm thick and plies at +45° and −45° are 0.23 mm thick each.

The shear web is a sandwich panel made of Gurit Corecell A500 between glass/epoxy skins. On the blade surface, there is also a layer of gelcoat (0.51 mm thick) and a ply of chopped strand mat (CSM, glass fiber with epoxy vinylester, 0.65 mm thick). A methacrylate adhesive is used to bond the aerodynamic skins and shear web together. Table 3 shows material properties used for blade design. Note that all material strengths of Table 3 have been divided by a safety factor of 3.0 (according to the IEC 61400-2 standard) when entered in the finite element model exept for the fatigue load case where the safety factor was 10.

Figure 4 shows the geometric model and the mesh of the inner part of the blade. The mesh is mostly made of four node shell elements. The chord length is discretized with about 25 elements and the size of elements is reduced towards the blade tip to get element aspect ratios as close as possible to 1. The finite element model has a total of 21 553 nodes and 21 536 elements.

The aerodynamic loads were applied in the model as pressure on the blade's surface elements. These pressures were computed using Matlab routines to reproduce the aerodynamic load distribution computed by FAST. The gravitational and inertial loads were applied as volume loads in the finite element model using the wind turbine operating conditions (rotor and nacelle rotational speed and acceleration, blade azimuthal position and blade pitch) computed by FAST.

The finite element analysis software OptiStruct [6] was used for the structural design of the blade. In the early stages of the design process, optimization capabilities of OptiStruct were used. When defining the layup for each blade regions (different colors in Figure 4a, the SMEAR option was enabled, allowing to define only one ply of each orientations (0° and ±45°). The SMEAR option homogeneizes the materials in-plane properties through the thickness so that the stacking sequence is ignored. The thickness of theses superplies for each blade regions was used as design variables. The objective of the optimization problem was to minimize the blade mass while ensuring composite strength, avoiding buckling and limiting the blade tip deflection to 12 % of the rotor radius for each of the design load cases. For more details about this methodology, see section 8 of a previous paper by Forcier and Joncas [7].

Once this optimization process was completed, the design was adjusted manually to take into account manufacturing constraints that were not included in the optimization run (e.g., discrete ply thickness, increasing layup thicknesses towards blade root, ply sequence). The final blade composite layup is presented in Table 4.

The blade root to hub attachment system is based on a concept used for the Sandia National Laboratories' Blade System Design Studies [8]. M16×2 steel threaded studs are inserted into 15 mm thick steel half-rings at the blade root and incorporated in the blade composite laminates prior to infusion. The length of the studs inside the blade is 155 mm and the studs are tapered for the last 115 mm (see Figure 5). An experimental validation of this concept has been done by a tension test on a steel stud embedded in a composite laminate similar to the blade root laminate. This assembly succesfully resisted to the design load.

6 Blade manufacturing

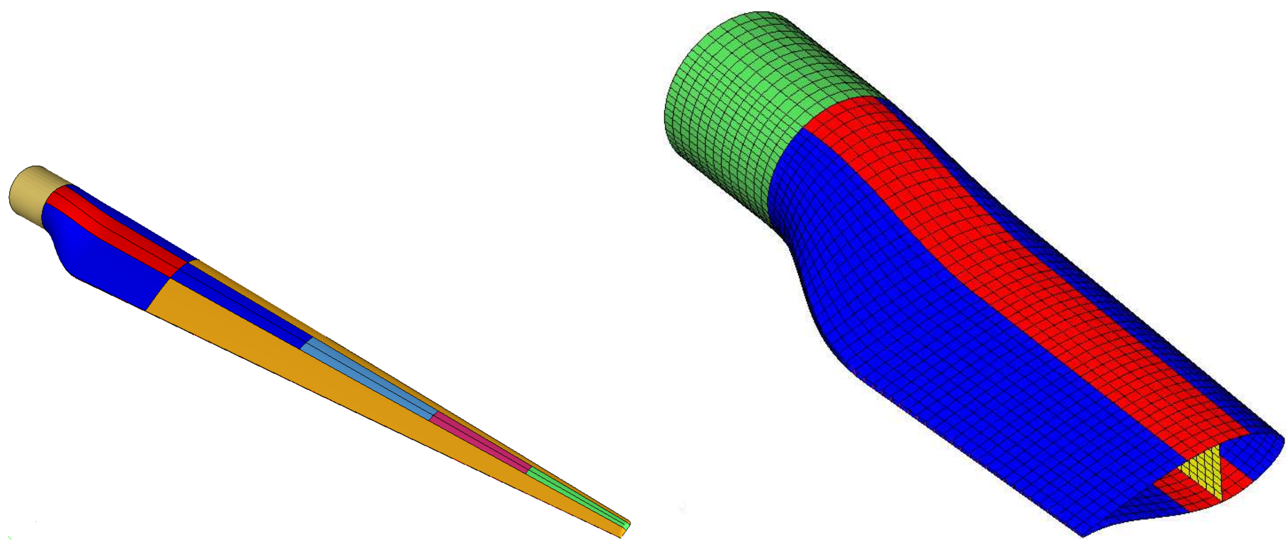
The blades have been manufactured at Composites VCI (Saint-Lin, Québec, Canada). Both aerodynamic skins were manufactured separately in renshape molds using vacuum resin infusion. A layer of gelcoat was first applied on the mold and a ply of chopped strand mat (CSM) was laminated by hand layup. Glass fibre plies were then placed incorporating the steel parts at root as shown in Figure 5a–c. Near the blade root, where the composite laminate is thick, both skins were bonded together using a but joint. Counter molds were used to get a good flat surface for bonding (one counter mold shown on Figure 5a–c). In addition to these counter molds (two for the upper surface skin and two other for the lower surface skin) an other counter mold was installed on the lower surface mold along the blade leading edge to create a lap joint as shown in Figures 3 and 5e. At the trailing edge, no counter mold was necessary as both skins were bonded on the internal surface of each other.

Once both aerodynamic skin were infused, they were

Table 3: Material properties used in the finite element models.

			UD[1]	CSM[2]	Core[3]	Gelcoat[2]
Longitudinal elastic modulus	E_1	[MPa]	38954	9650	72.5	3440
Tranverse elastic modulus	E_2	[MPa]	14538	9650	72.5	3440
Major Poisson ratio	ν_{12}		0.29	0.30	0.39	0.30
Shear modulus	G_{12}	[MPa]	4239	3860	26	1380
Longitudinal tension strength	S_1^T	[MPa]	776	124	1.3	-
Longitudinal compression strength	S_1^C	[MPa]	522	-	0.9	-
Transverse tension strength	S_2^T	[MPa]	54	124	1.3	-
Transverse compression strength	S_2^C	[MPa]	165	-	0.9	-
Shear strength	S_{12}	[MPa]	56	-	1	-
Density	ρ	[kg/m^3]	1884	1670	92	1230
Ply thickness	t	[mm]	*	0.65	19.05	0.51

* 0.50 mm for 0° plies and 0.23 mm for +45° and -45° plies.
[1] From the Optimat Blades project [4].
[2] From the WindPACT turbine design studies [5].
[3] From material technical data sheet.



(a) (b)

Figure 4: Blade model. Regions with different colors have different composite laminates. (a) Surfaces. (b) Mesh of the inner part.

Table 4: Blade layup.

Blade region, distance from blade root	Laminate
Blade root circular region	
0 mm–210 mm	[GC/CSM/$(+45/\text{-}45)_3/0_6/(+45/\text{-}45)_3$/*/ $(+45/\text{-}45)_3/0_8/(+45/\text{-}45)_3$]
Spar cap, from 15 % to 45 % of chord length	
210 mm–960 mm	[GC/CSM/$(+45/\text{-}45)_2/0_{11}/(+45/\text{-}45)_2$]
960 mm–2560 mm	[GC/CSM/$(+45/\text{-}45)_2/0_{10}/(+45/\text{-}45)_2$]
2560 mm–3160 mm	[GC/CSM/$(+45/\text{-}45)_2/0_6/(+45/\text{-}45)_2$]
3160 mm–3776 mm	[GC/CSM/$(+45/\text{-}45)_2/0_2/(+45/\text{-}45)_2$]
Aerodynamic shells, outside spar cap	
210 mm–960 mm	[GC/CSM/$(+45/\text{-}45)_2/0_{11}/(+45/\text{-}45)_2$]
960 mm–3776 mm	[GC/CSM/$(+45/\text{-}45)_2/0_1/(+45/\text{-}45)_2$]
Shear web	
210 mm–3776 mm	[$(+45/\text{-}45)_3$/Core/$(+45/\text{-}45)_3$]

* Steel studs or 0° unidirectional glass-epoxy filler.

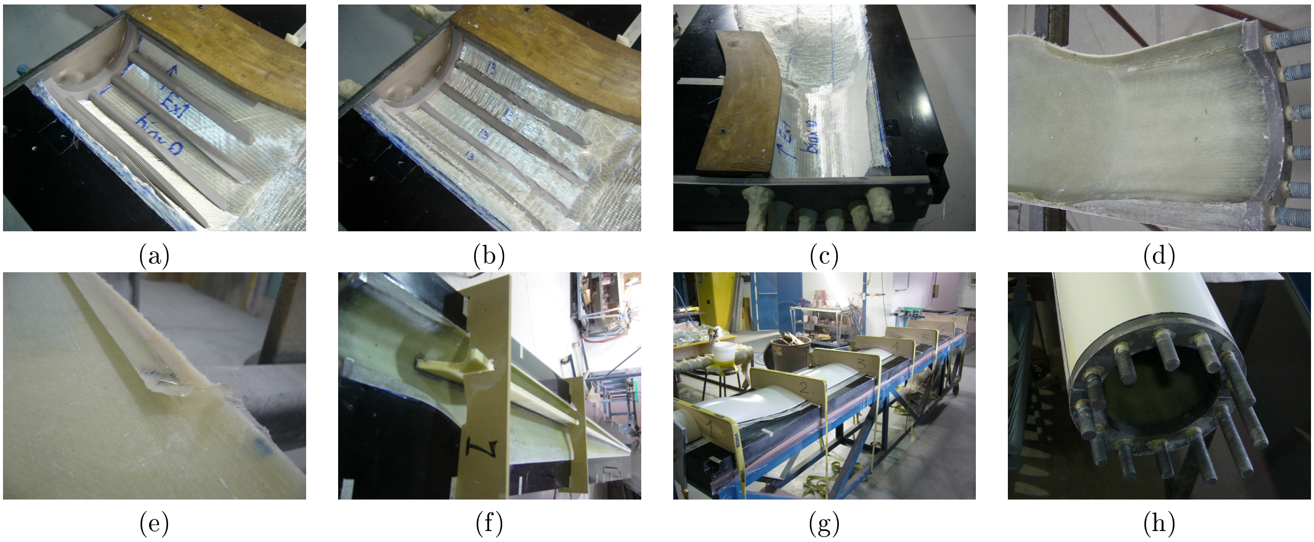


Figure 5: Blade manufacturing: (a–c) blade root layup; (d) infused lower surface; (e) bonding lip on lower surface's leading edge; (f) bonding of shear web on lower surface, nine positioning jigs are used (only two shown); (g) bonding of the upper surface on the lower surface and shear web assembly; (h) close view of the assembled blade root.

trimmed and the shear web was bonded to the lower surface as shown in Figure 5f. The shear web was cut out from an infused flat sandwich panel. The upper surface was then bonded to the assembly of lower surface and shear web as shown in Figure 5g. Figure 5h shows the bonded blade near the root region.

Once assembled, the blade was finished and post-cured at 65°C for 7 hours.

The final blade mass is 28 kg.

7 Blade testing

To validate the structural design, a blade was tested according to the IEC standard on structural testing for wind turbine blades [9]. The blade was cantilevered at root and loaded with sand bags as shown on Figure 6. The blade was instrumented with strain gauges and deflection was measured during the test.

The test load was defined using the flapwise bending moment distribution of the flapwise critical load case simulated with FAST. This load distribution was then multiplied by 1.35, the safety factor on loads for blade design, and by 1.10, the safety factor for test according to the IEC standard on blade testing [9]. The sand bag distribution for the different load increments were computed to reproduce this bending moment distribution taking into account the self weight of the blade.

As stated earlier, the critical flapwise load case is in the opposite direction of the normal operating aerodynamic loads. The blade was therefore tested with the upper surface upward and load applied downward. The blade was first tested up to 100 % of the test load, then, it was turned to applied the same load distribution but in the opposite direction (in the aerodynamic loads direction for normal operation conditions). The blade also successfully resists to this load case.

The blade was then repositioned in its first orientation and the load level was increased up to 150 % of the test load without any noticeable damage.

When comparing the test results to the numerical results, we can see first, as shown in Figure 7, that the blade tip deflections measured during the test at different load levels were in good agreement with the numerical results. All differences are below 4 %.

Figure 8 shows the longitudinal normal strain on the blade surface at 100 % of test load. Extracting the strain values along the spar caps center lines allows to compare with strain gage measurements (Figure 9). Differences between experimental and numerical results are higher than those of the deflection measurements but are still in relatively good agreement. These differences can be explained by the fact that deflections are global measures while strains are more affected by local phenomena that could be missed by the finite element model. Inaccuracy in the position of the strain gages could also explain the differences observed.

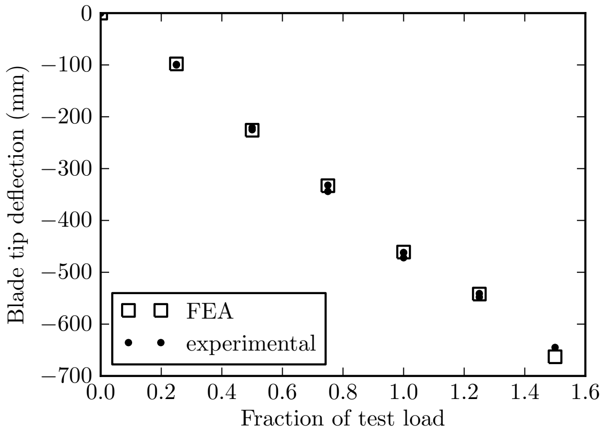


Figure 7: Blade tip deflection at different fraction of the test load.

Table 5: Blade modal analysis results.

Modes	Frequency [Hz]		Error (%)
	Test	FEA	
1	6.39	6.43	0.63
2	16.1	16.2	0.62
3	20.1	19.5	-2.99

A modal analysis was made by deflecting and suddenly releasing the blade tip. An accelerometer on the blade was used to measure the vibration induced. The Fourier transform of the acceleration signal allows to compute the natural frequencies of the structure. Table 5 shows these results and the frequencies computed with the finite element model. The differences between numerical and experimental results are limited to 3 % for the first three eigenmodes.

8 Conclusion

The objective of the small wind turbine project funded by Wind Energy Strategic Network was to design and build a 10 kW wind turbine. The aerodynamic design of the blade was made using blade element momentum theory and structural loads were obtained from aeroelastic simulations using the NREL's FAST code. The structural design of the glass/epoxy composite blade was made according to the IEC 61400-2 standard using the Optistruct finite element software. During the early stages of the design process, the optimization capabilities of this software was used. The blades were manufactured by vacuum infusion

Figure 6: Blade validation test.

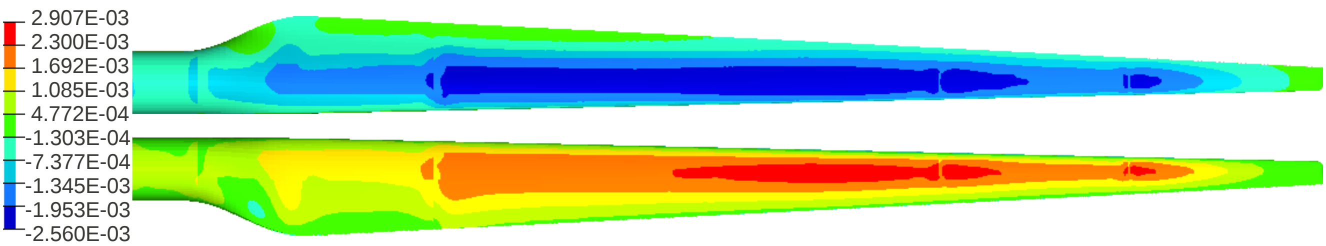


Figure 8: Contour plot of longitudinal normal strain on the blade surface at 100 % of test load. Upper image shows the lower surface and lower image shows the upper surface.

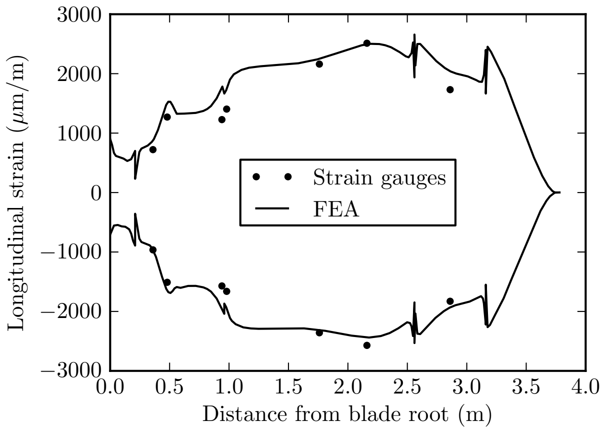


Figure 9: Variation of longitudinal strain along the center of the spar caps at 100 % of the test load.

of shear web and both upper and lower aerodynamic skins that were bonded together in a subsequent step. A static test showed that the blade is able to resist to the design load without any damage and deflection and strain measurements aggree well with the numerical results. A modal analysis of the blade also showed good agreement with the numerical analysis.

As part of a Ph.D. project, this blade design will be tested soon at typical cold climate temperature to study the blade structural behaviour under these conditions.

Acknowledgments

The authors would like to thanks the Natural Sciences and Engineering Research Council of Canada's Wind Energy Strategic Network (NSERC/WESNet) for funding this project. We also want to thank Composites VCI for the development of the blade manufacturing process.

References

[1] W. A. Timmer and R. P. J. O. M. van Rooij. Summary of the Delft University wind turbine dedicated airfoils. *Journal of Solar Energy Engineering*, 125:488–496, 2003.

[2] J. M. Jonkman and M. L. Buhl Jr. FAST user's guide. Technical Report NREL/EL-500-38230, National Renewable Energy Laboratory, Golden (Colorado, United States), 2005.

[3] International Electrotechnical Commission. *Wind Turbines - Part 2 : Design requirements for small wind turbines.* IEC 61400-2, International Electrotechnical Commission, Geneva (Switzerland), 2nd edition, 2005.

[4] R. Nijssen. OptiDAT Database Reference Document. Technical Report OB_TC_R018 rev. 005, Optimat Blades, 2006. database available at `http://www.wmc.eu/optidat_files/Optidat%20UPWIND%2010_2_2011.zip`, accessed: 13 Marsh 2013.

[5] D. A. Griffin. WindPACT turbine design scaling studies technical area 1 – composite blades for 80- to 120-meter rotor. Technical Report NREL/SR-500-29492, National Renewable Energy Laboratory, Golden (Colorado, United States), 2001.

[6] Altair Engineering, inc. *Optistruct (version 11.0).* Troy (Michigan, United States), 2012.

[7] L.-C. Forcier and S. Joncas. Development of a structural optimization strategy for the design of next generation large thermoplastic wind turbine blades. *Structural and Multdisciplinary Optimization*, 45:889–906, 2012.

[8] D. S. Berry. Blade System Design Studies Phase II: Final Project Report. Technical Report SAND2008-4648, Sandia National Laboratories, Albuquerque (New Mexico, United States), 2008.

[9] International Electrotechnical Commission. *Wind turbine generator systems - Part 23: Full-scale structural testing of rotor blades.* IEC TS 61400-23, International Electrotechnical Commission, Geneva (Switzerland), 2001.