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Spar shape optimization of a multi megawatts composite wind turbine blade

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Abstract : We currently notice a substantial growth in the wind energy sector worldwide. This growth is expected to be even faster in the coming years. This means that a massive number of wind turbine blades will be produced in the forthcoming years. There is a large potential for materials savings in these blades. The analysis of designed blade is done in dynamic loading. Five types of spars cross-section are taken in this work. The blade and spar are of composite material. The Finite element modal analysis of designed blade is done in ABAQUS. A numerical work has been used to address the most adequate spar shape and to get an understanding of the complex structural behavior of wind turbine blades. Five different types of structural reinforcements helping to prevent undesired structural elastic mechanisms are presented. Comparisons of the eigenfrequencies observed in the full-scale tests are presented and conclusions are drawn based on the mechanisms found..

Mots clés : Wind turbine blade, composites, shear web optimization, modal analysis, FEA

1. Introduction

The energy problem we are facing today is articulated around two main drivers: supply and greenhouse gas emissions. Renewable energy sources are an inevitable part of the solution, and wind energy is, at the moment, the fastest growing installed production technology.
Commercial wind turbines have developed consistently in size over the last thirty years, largely for economic reasons in an attempt to reduce the electricity production cost. This is due to the fact that wind speed – and hence wind power capture – increases with altitude and that reducing the number of individual turbine units helps to reduce the overall cost of a wind farm, especially offshore. The largest current machine has a rated output of 5MW and a rotor diameter of 124m and so the question arises as to what the ultimate limits on size might be.
In all cases, wind turbine blades have pure strength requirements. A static case can, for instance, be calculated on the basis of a 50-year return period gust, while fatigue strength for a 25-year lifetime implies cycle numbers of the order of 107. Another crucial requirement relates to the blade stiffness, since at all times a minimum clearance must be ensured between the blade tip and the turbine tower. The increase in diameter also makes the rotor and blade mass related requirements more severe. Not only do the blade root and the rotor hub need to sustain the static loads (the 62m world-largest blade weighs ~18T), but the nacelle structure, tower and foundations also need to sustain the whole machine dynamics. For a complete discussion of design requirements, interested readers can refer to Burton et al. [1].
Large wind turbine blades are typically manufactured with thin skins made from composite materials. Glass fiber/epoxy and wood laminates/epoxy are the most typical materials, but carbon fiber is also increasingly used. They are usually constructed from several parts glued together –compressive side, tensile side and shear webs. Their external geometry is fairly complex, made of 3D surfaces resulting from the aerofoil sections put together with varying twist angles, chord lengths and pitch axis locations. Regarding the internal structure, the manufacturing methods often result in thick adhesive joints in key structural locations and this is reflected in the models by 3D adhesive mesh elements. Finally, the materials used are highly anisotropic. The work conducted here notably takes advantage of the new capabilities of Abaqus v6.9.
This paper describes the creation of a numerical model which describes parametrically the geometry of the blade with composite materials for wind turbines of 5MW.

1. Blade geometry

The main objective in the design of wind turbines is to find a rotor that meets the basic conditions requested. The most important condition is to get a rotor to deliver output power required at a particular speed. For this, the first assumption of the aerodynamic rotor is its diameter, which can be roughly estimated power coefficient. In

addition, it is necessary to take into account the importance of the geometry of the rotor, taking into consideration the most important, the aerodynamic performance, strength and stiffness conditions, and costs.
However, power generation through wind turbines also play a decisive role in the design of the aerodynamics of the rotor, which is influenced by other parameters such as power generator and control system.
It wants to generate a power of 5MW with a blade of 48m long, aerodynamic characteristics were obtained through a study of marketing match, where they had the distribution curves of chord, the twist, the pre-bend, thickness, and the distance between the pitch axis and the trailing edge of several blades used in the market, and averaged to obtain those that were used to create the numerical model.

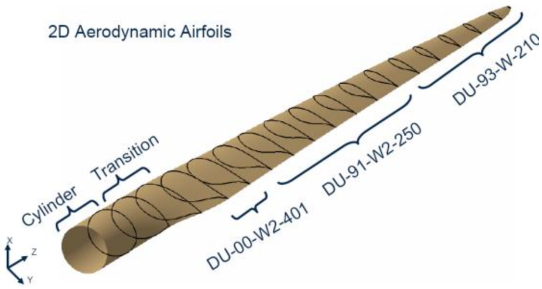


Figure 1 : Different Airfoils along the blade.

The blade that we will study is assembled on a three-bladed of offshore wind turbine which delivers a maximum power of 5MW, figure 1. The general specifications of the studied blade are given in Table 1.

Tableau 1 : General specifications of the blade

Length (mm)	48000
Maximum cord (mm)	3932
Position twists maximum (mm)	R9000
Fluid speed upstream of blade (m/s)	25
Angular velocity (rpm)	15,7
Frequency of solicitation: Fr (Hz)	0,26
Power (MW)	5

1.1. Choice of the profile
A preliminary calculation with “HELICIEL” software enabled us to establish an adequate profile answering the specifications of table 1. Figure 2 gives a schematic representation of initial profile NACA 4412 selected.

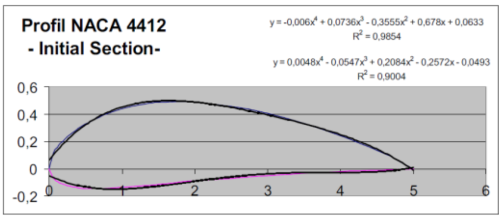
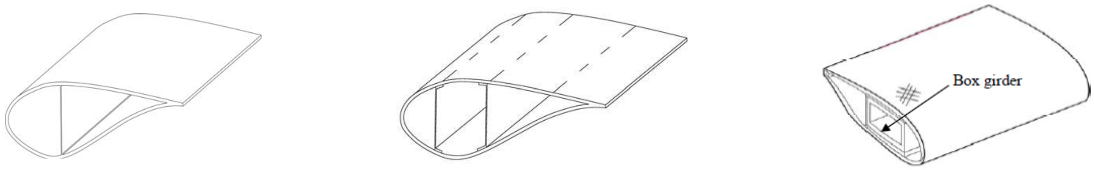


Figure 2 : Profile NACA 4412

1.2. Extrados, intrados and spar
The design of the aerofoil of a wind turbine blade is a compromise between aerodynamic and structural (stiffness) considerations. Aerodynamic considerations are dominating the design of the outer two thirds of the blade while structural considerations are more important for the design of the inner one third of the blade.
Structurally the blade is typically hollow, with the outer geometry formed by two shells: one on the suction and one on the pressure side. To transfer shear loads, one or more structural webs are fitted to join the two shells together, see Figure 3a and Figure 3b. A load carrying box girder is used in some blade designs, see Figure 3c. Such designs correspond to blades with two webs.



(a) *(b)* *(c)*

Figure 3 : Sketches of different blade concepts

2. FE modeling and structural design optimization

Only a limited number of publications on Finite Element (FE) modeling and structural analysis of wind turbine blades are available in current literature. Most available research done on FE-analysis of wind turbine blades are global FE-models of the entire blade where strains, global deflections and Eigen frequencies are found [2-6].

There has been comprehensive research in failure modeling which take interlaminar crack growth into consideration [7-8]. Interlaminar crack growth has been studied very intensively in other industries the last two decades, and has recently become an important area of the research related to the wind turbine industry.

A big advantage of using FEM is that, once the model is set up and calibrated, complex load cases representing actual wind conditions can be analyzed. Only idealized loads can be imposed in a full scale test and in this paper the modal analysis case is evaluated. The FE model of the wind turbine blade with a NACA 4412 airfoil is created using ABAQUS.

2.1. Shear web transverse placement

The transverse placement of the shear-webs within the aerofoil sections naturally influences the structural properties of the assembly. Due to the twist angle variations along the blade, a bending loading state always introduces torsion in some sections of the blade. Such torsion modifies the angle of attack of the aerodynamic surfaces, in turn causing a modification in loading – such a phenomenon is generally described as aero-elastic.

The finite element method (FEM) has traditionally been used in the development of wind turbine blades mainly to investigate the global behavior in terms of, for example, eigenfrequencies, tip deflections, and global stress/strain levels. This type of FE-simulation usually predicts the global stiffness and stresses with a good accuracy. Local deformations and stresses are often more difficult to predict and little has been published in this area. One reason is that the highly localized deformations and stresses can be non-linear, while the global response appears linear for relatively small deflections. Another factor is that a relatively simple shell model can be used for representing the global behavior, while a computationally more expensive 3D-solid model may be necessary to predict this localized behavior. Even with a highly detailed 3D solid model it would rarely be possible to predict deformations or stresses accurately without calibration of the FE-model. This calibration is necessary due to large manufacturing tolerances. Features such as box girder corners and adhesive joints often differ from specifications. Geometric imperfections are often seen and can cause unexpected behavior, especially relating to the strength predictions but also the local deformations can be affected. In this paper, box girder corners were not modeled in detail using solids.

The influence of the shear-web placement on the blade mass, bending stiffness and bending-torsion coupling is studied in this example. Five different geometries are examined as shown in Figure 4. In each one, the shear-webs are moved in opposite directions, from being very close to each other to being near the leading and trailing edges.

- ✓ (1) Blade with web of form T (39% length of the cord)
- ✓ (2) Blade with one shear web (39% length of the cord)
- ✓ (3) Blade with two shear webs (between 49% and 29% length of the cord)
- ✓ (4) Blade with three shear webs (between 49% and 29% length of the cord)
- ✓ (5) Blade with web of form H (between 49% and 29% length of the cord)

Figure 5 shows the various models which will be useful for the study of optimization of the geometrical form of the webs.

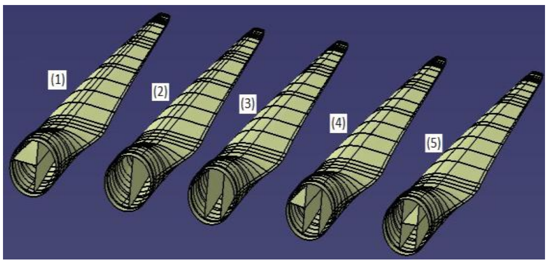


Figure 4 : Blades with different shear-web

2.2. Materials and lamination strategy

There is a wide range of materials and manufacturing techniques utilized in the wind turbine industry today. The material combinations used are predominantly composite laminates with embedded threaded steel rods in the root section connecting the blade to the hub in a bolted connection Polyester, vinylester and epoxy resins are common, matched with reinforcing wood, glass, and carbon fibers. Some designs integrate carbon and glass fiber as well as birch and balsa wood.

Both the materials and the lamination strategy were selected through the UpWind data. UpWind is a European project funded under the Sixth Framework Program of EU. Its task is the design of powerful wind turbines (8-10 MW) with both onshore and offshore. The materials used, in principle, were 5 different types: UD, Triax, R4545, Foam and Webs, whose properties are shown below in the table 1.

The mechanical properties of composite materials are given in table 2:

Tableau 2 : Mechanical properties of materials used

	Orthotropic Composites			**Isotropic Composites**	
	UD	***TRIAX***	***R4545***	***SKIN FOAM***	***ADHESIVE***
E_{11} (MPa)	38887	24800	11700	256	3000
E_{22} (MPa)	9000	11500	11700	256	3000
G_{12} (MPa)	3600	4861	9770	22	1150
ν_{12}	0.249	0.416	0.501	0.3	0.3
ρ (kg/m³)	1869	1826	1782	200	1200

1.1. Mesh part

For the 5 developed models, shell elements type S4R was used. Below characteristics of the 5 models with 200 mm a mesh size of elements. Solid elements C3D8R were used to mesh the adhesive (model 4 and 5). Below, an example of the mesh carried out for model 1: blade with only one web, Figure 5.

Figure 5 : Mesh of model

2. Modal analysis

According to the structure chosen, the blade will be able to have a different mechanical response. It is necessary to apprehend the effects of the action of the wind. For that, one identifies by the experiment and/or finite element analysis what one calls the modes which translate the way in which will become naturally deformed the blade under loading. Each one of these modes is defined by a frequency, a damping and a modal form:

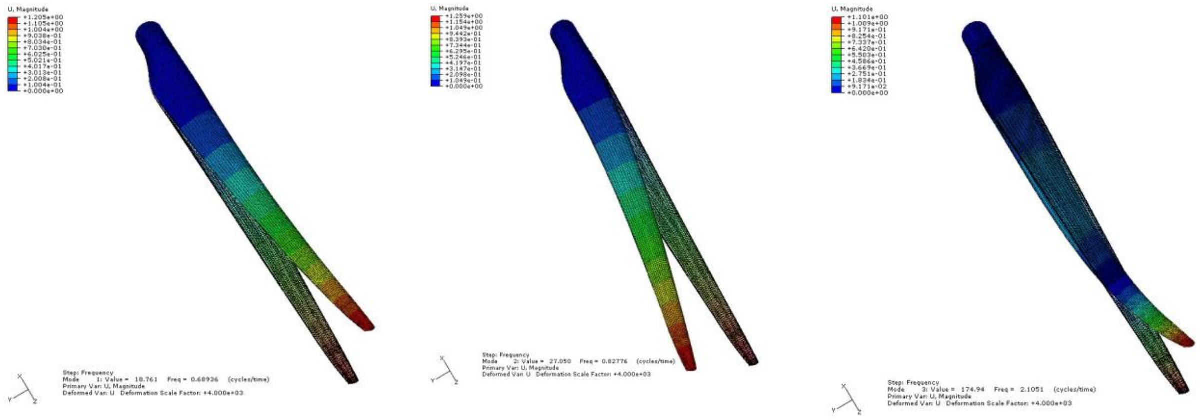
In our case, these modes are calculated by the finite element method with the computer code “Abaqus”. This calculation is carried out for the 5 models with two boundary conditions:

- The root is clamped.
- No condition at the blade tip.

The natural frequencies, obtained from the modal analysis, are presented in Table 3. We are interested here to analyze the first 3 modes. For illustration, the mode shape results, associated with the lowest 3 blade natural frequencies, are illustrated in Figure 6.

Tableau 3 : First three modes and eigenfrequencies

Model	**First mode**	**Second mode**	**Third mode**
1	0,76632	0,88886	2,2711
2	0,68936	0,82776	2,1051
3	0,66633	0,80179	2,0397
4	0,71308	0,8521	2,1566
5	0,69261	0,83065	2,1157



(a) Mode 1 *(b) Mode 2* *(c) Mode 3*

Figure 6 : Eigen frequencies of model 2

According to standard GL Wind2003 (Germanischer Lloyd Wind Energy GMBH, 2005), the condition below must be checked to avoid the phenomenon of resonance:

$$F_r / F_{0,n} \leq 0.95 \qquad (1)$$

with :

$F_{0,n}$: the n eigenfrequency of the structure

F_r : Frequency of solicitation, $F_r = 0.26Hz$.

One applying this condition for the first two modes, one concluded that the effect of resonance does not occur for the 5 models, table 4.

Tableau 4 : Computation results of the resonance effect

Effect of resonance for the 1st mode (Flapwise) & 2nd mode (Edgewise)		
Model	**$F_r/F_{0,n}$**	**$F_r/F_{0,n}$**
1	0,339	0,292
2	0,377	0,314
3	0,390	0,324
4	0,364	0,305
5	0,375	0,313

3. Conclusion

The performed modal analysis gives estimates of lower 3 natural frequencies and mode shapes, for the investigated 48m blade. The results are based on finite elements method performed in different cross sections along the blade. The estimated natural frequencies and mode shapes have subsequently been compared to check that the resonance mode of the system is not reached. Natural frequencies and mode shapes, obtained from a FE model of the investigated blade, are performed in order to evaluate the state-of-the-art blade modeling capacity and in addition to gain inspiration for further improvements.

The present investigation has demonstrated that essential dynamic properties of wind turbine blades, like natural frequencies and mode shapes, can be numerically determined by use of the modal analysis technique. Blades with different spar geometry have been considered and the most appropriate of these has been selected. Although the comparison is based only on FE results on a 48m blade, the recommendations given are believed to be valid for other types (sizes, designs, ...) of wind turbine blades as well.

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