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Structural analysis of horizontal axis wind turbine blade

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Abstract. The wind turbine blade is a very important part of the rotor. Extraction of energy from wind depends on the design of blade. In this work, the analysis is done on a blade of length 38.95 m which is designed for V82-1.65 MW horizontal axis wind turbine (supplied by Vestas). The airfoil taken for the blade is NACA 634–221 which is same from root to tip. The analysis of designed blade is done in flap-wise loading. Two shapes of the spar are taken, one of them is of square shape and the other one is combination of square and cross shape. The blade and spar are of the same composite material. The Finite element analysis of designed blade is done in ANSYS. This work is focused on the two segments of blade, root segment and transition segment. Result obtained from ANSYS is compared with the experimental work.

Keywords: design; material; chord; twist; blade

1. Introduction

Wind turbines are subjected to very specific loads and stresses. Due to the nature of wind, loads are highly variable. Varying loads are more difficult to handle than static loads because the material becomes fatigued. Moreover as a working medium the air is of low density so that the surface required for capturing energy must be large. When designing a wind turbine, the aim is to attain the highest possible power output under particular atmospheric conditions and this depends on the shape of the blade. The change of the shape of blade is one of the methods to optimize stiffness and stability, but it may influence aerodynamic efficiency of wind turbine. Dynamic and mechanical properties can also be changed by modifying the composite material of wind turbine blade.

Jensen *et al.* (2006) worked on structural analysis and numerical simulation of 34 m composite wind turbine blade, the material taken in his work is Glass- Epoxy. Jensen *et al.* (2006) observed the ovalization of the load carrying box girder in the full scale test. A global non-linear FE-model of the entire blade was prepared and the boundaries to a more detailed sub-model were extracted. The FE-model was calibrated based on full-scale test measurements. A probabilistic model for analysis of the safety of a wind-turbine rotor blade against failure in ultimate loading is presented by Ronold *et al.* (2000). In his work Ronold (2000) only considered the failure in flap-wise bending during the normal operating condition of the wind turbine. The model is based on an

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extreme-value analysis of the load response process in conjunction with a stochastic representation of the governing tensile strength of the rotor blade material. The probability of failure in flap-wise bending of the rotor blade is calculated by means of a first-order reliability method, and contributions to this probability from all local maxima of the load response process over the operational life are integrated. Jureczko *et al*. (2005) took the problem of the multi-criteria optimum design of wind turbine blades and developed a computer program package that would enable optimization of wind turbine blades with regard to a number of criteria.

The study of Jeng *et al.* (2010) presents a combined analytical and finite element beam (CAFB) model with an inclination angle correction to solve the non-prismatic, blade-like FRP beam problem. Grujicic *et al.* (2009) developed a computer program which can automatically generate both a geometrical model and a full finite-element input deck for a given single HAWT-blade with a given airfoil shape, size, and the type and position of the interior load-bearing longitudinal beam/shear-webs. Grujicic *et al.*(2009) introduced a multi-disciplinary design-optimization procedure and he used it for the development of cost-effective glass-fiber reinforced epoxy-matrix composite 5 MW horizontal-axis wind-turbine (HAWT) blades. The study of Kong *et al.* (2004) proposes a structural design for developing a medium scale composite wind turbine blade made of E-glass/epoxy for a 750 kW class horizontal axis wind turbine system. Mandell *et al.* (1998) used the database and analysis methods to predict wind turbine blade structural performance for stiffness, static strength, dynamic response, and fatigue lifetime. Lars *et al.* (2005) performed Full scale experiments of the blade from static loading to collapse and are used as reference for verifying the finite element shell model used in this work.

In this work a blade of length 38.95 m for V82-1.65 MW horizontal axis wind turbine (supplied by Vestas) is designed on the basis of Glauert's optimal rotor theory. A computer program is developed for getting the dimension (Twist, chord and thickness). This work focuses on the deflection of cap and web of spar at root and transition segment of the blade when flapwise loading is applied on the blade. In the first part of this work square shape spar is taken for blade and for verification author compared his result with the results of Jensen *et al.* (2006) for the same segment (root and transition). In the second part of this work the spar taken is the combination of two shapes of spar, first one is of square shape and the other one is of cross shape as we can see in Fig. 6. Finite element analysis of the blade structure is done in ANSYS software. In this work the material taken is E-Glass/Epoxy pre-preg material and the properties taken from Brøndsted (2005). Results obtained from ANSYS although preliminary, looked very promising and confirmed that the proposed spar is valid for blade structure. Experimental validation for blade with modified spar is very complicated and expensive but it would be required.

2. Computational methods

The finite element method (FEM) is a method used for finding the approximate solution of partial differential equations (PDE) that handle complex geometries (and boundaries), such as wind turbine blade with arbitrary cross-sections, in a quite simple manner. The finite element method (FEM) is very important tool in the development of wind turbine blades for determining the global behavior in terms of eigen frequencies, tip deflections, and global stress/strain levels respectively. The field region is divided into elements of various shapes, such as triangles and rectangles, allowing the use of an irregular grid. The FE-simulation generally formulates the global stiffness and stresses with a high-quality accuracy. Local deformations and stresses are lot more difficult to predict and little work has been done in this area. In case of wind turbine blade analysis highly localized deformations and stresses are found to vary in non-linear fashion, while on the other hand the deflections are small and vary linearly. Besides this simple shell model can be used in place of 3D solid model for prediction of local behavior because 3D solid model is computationally more expensive. Still by using detailed 3D solid model it would rarely be possible to predict deformations or stresses accurately without calibration of the FE-model. This calibration is needed due to large manufacturing tolerances. Features such as box girder corners and adhesive joints often vary from specifications. Geometric imperfections are often seen and can cause unexpected behaviour, especially relating to the strength predictions but also the local deformations can be affected. A main benefit of using FEM is that, once the model is set up and calibrated, complex load cases representing actual wind conditions can be analyzed. The applied loads are suitable for full scale test when they are assumed to be ideal. In the present work critical flap-wise load case is evaluated. The FE model of the wind turbine blade with a NACA 63_4–221airfoil is created using APDL language in ANSYS.

3. Twist, chord and thickness distribution

The twist of a wind turbine blade is defined in terms of the chord line. It is a synonym for the pitch angle. However the twist defines the pitch settings at each station along the blade according to the local flow conditions. The pitch angle (β) is large near the root (where local speeds are low), and small at the tip (where local speeds are high). The apparent wind angle changes along the blade due to increase in blade speed with increasing distance outboard. Hence to maintain optimum angle of attack of the blade section to the wind, it must be twisted along its length. According to Hau (2006) the twist distribution is maintained such that the lift coefficient will be maximum at every station. Chord direction is perpendicular to the span direction and lies in the plane extending through the leading edge and the trailing edge. A shoulder is the point where chord is maximum and it is minimum at the tip of the blade. Stresses are maximum at the blade root so that the blade root is the thickest portion of the blade. The thickness distribution is calculated in terms of the chord where the total thickness of the blade at any station will be a percentage of the chord length at that station. Fig. 1 shows the chord distribution for the blade. Figs. 2 and 3 shows the twist and thickness distribution for the blade. Both chord and thickness are reducing from root to tip. The chord is calculated on the concept used by Ryu (2004).

4. Blade properties

The wind-turbine blade is essentially a cantilever beam mounted on a rotating hub. The aerodynamic shape of the blade is formed by relatively thin outer shells. The loads acting on the blade are mainly supported by a longitudinal box-shaped spar. To reduce the maximum bending moments located at the blade root (the section where the blade is attached to the hub), wind turbine blades are generally tapered along the span. Tapering typically includes not only the blade cross section chord and thickness but also the thicknesses of the outer shells, spar caps and shear webs. This ensures that different blade sections experience comparable extreme loading (e.g., the maximum strain), so that no unnecessary local over-sizing is present. In addition to the taper, turbine blade generally possess a certain amount of twist along their length. Twist is beneficial

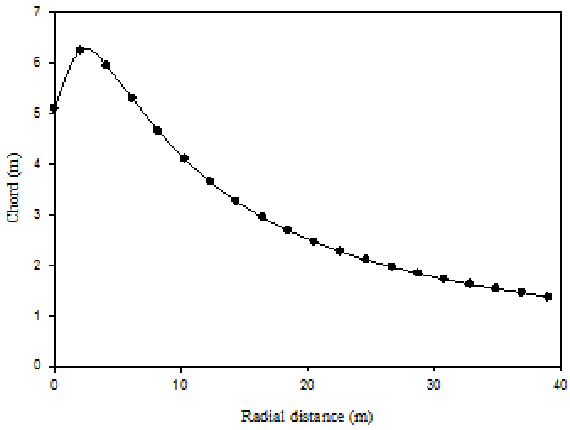

Fig. 1 Chord distribution

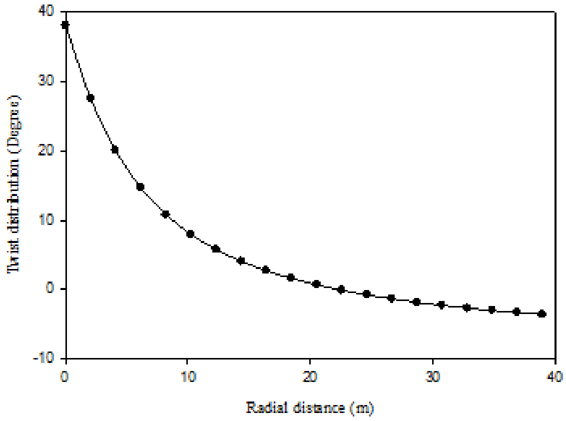

Fig. 2 Twist distribution

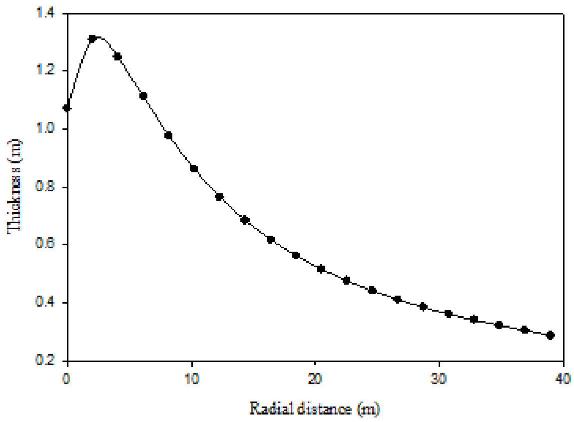

Fig. 3 Thickness distribution

with respect to lowering the torque required for self-starting of the rotor and for the attainment of the optimal effective wind attack angle during the wind turbine operation.

The aerodynamic profiles of wind turbine blades have vital control on aerodynamic efficiency of wind turbine. In this work, the length of the blade is 38.95 m and the analysis is done for two shapes of spar. According to wind energy project (2003) the location of the main spar with the location of the stiffening ribs will have the biggest effect on the bending modes of the blade. The model of blade (Fig. 4) made of shell element is used in this work. The blade is to be twisted around the elastic axis Centraltrykkeri (2002). The position of elastic centre can be varied by modifying the location of spars and its shape. The geometry of blade is modelled in ANSYS to obtain the required properties of the blade and position of spars. The blade is divided into 19 sections. Twist of the blade decides the value of aerodynamic loads, and also the direction in which the blade will vibrate. In this work the spar is also twisted according to airfoil. The blade with twisted spars is shown in Figs. 5 and 6.

5. Result and discussion

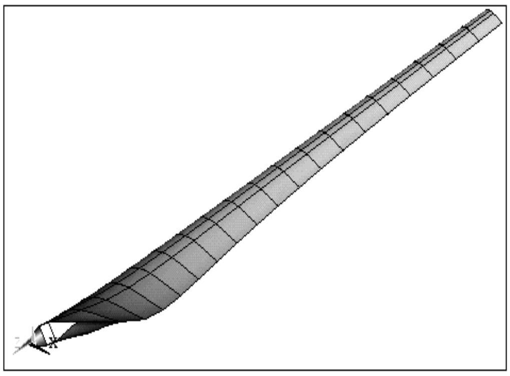

Fig. 4 Blade model

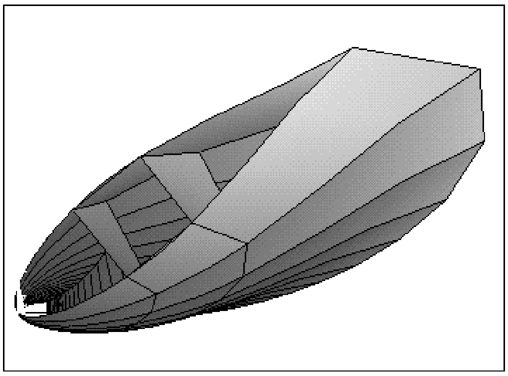

Fig. 5 Twisted blade with spar (Square)

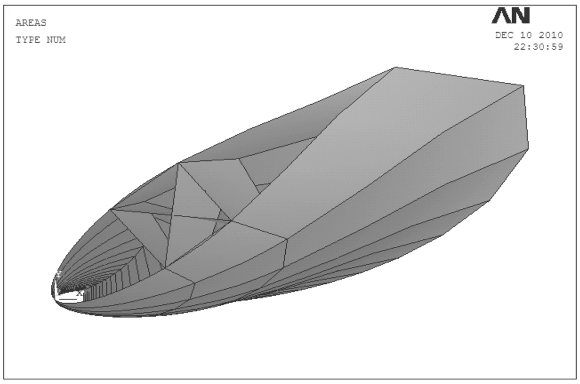

Fig. 6 Twisted blade with spar (Combined square and cross)

In the present work a blade with NACA 63_4-221 airfoil has been modeled and analyzed by using finite element software package ANSYS 12.0. In this analysis two shapes of spar are taken for modeling of blade, one of them is square and other one is combined (square and cross). The length of blade taken is 38.95 m while Jensen *et al*. (2006) worked on the blade of length 34 m. In order to compare the present work with experimental work (Jensen) difference in length the root and transition segment has been shifted proportionally. Jensen (2006) done his experimental work on the blade manufactured by SSP-Technology A/S. The SSP blade is made up of glass epoxy pre-perg material and is designed with load carrying box girder shown in Fig. 7. Fig. 8 is showing the blade with square shape spar which is used for comparison of deflection under flapwise loading with boundary condition of cantilever beam. Gravity load is not considered in this work and deflection has been measured in ANSYS. Jensen *et al*. (2006) used shell and brick element for modeling of blade while in present work complete model of blade has been prepared by using shell elements. The blade length is 38.95 m and the analysis is done on the two segments namely Root segment (0-4.1 m) and Transition segment (4.1-8.2 m). The created model of the blade with square shape spar consists of 141117 elements, 138139 nodes and 176 areas meshed and the blade consist spar of combined shape have 147197 elements, 142705 nodes and 214 areas meshed. The 8-noded shell 63 element type with 6 degree of freedom has been used with an element thickness provided 30 mm.

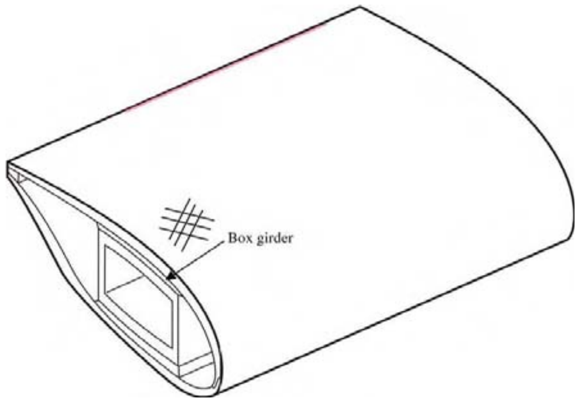

Fig. 7 Load carrying main spar (2006)

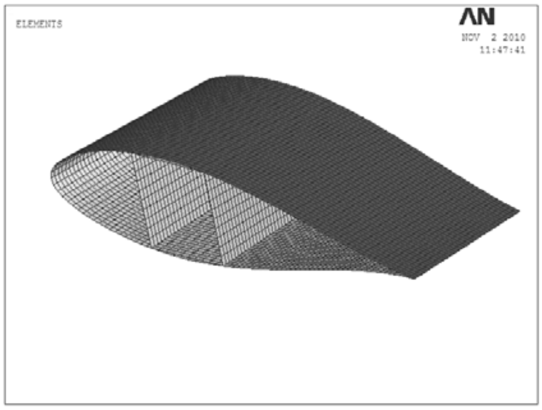

Fig. 8 Blade with load carrying spar (Square)

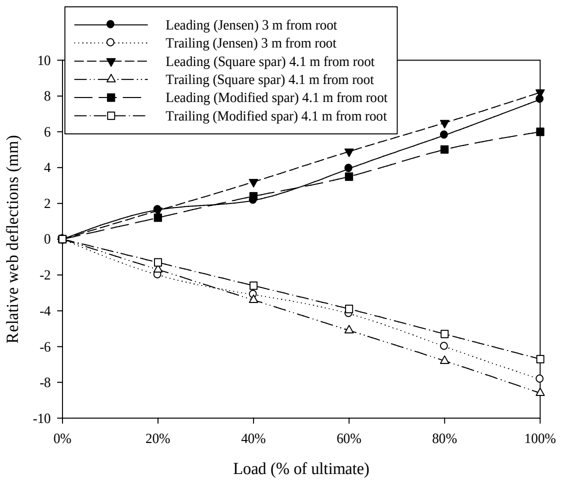

Fig. 9 Relative web deflection

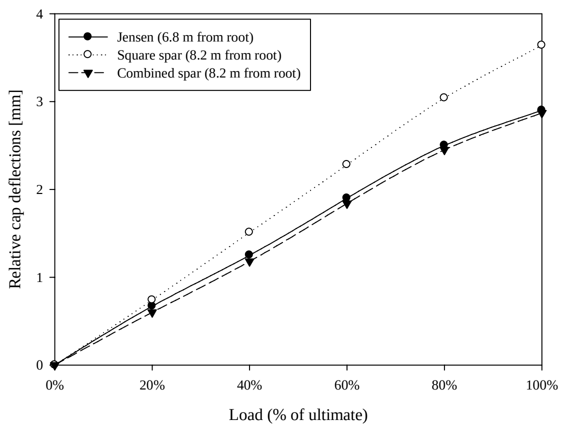

Fig. 10 Outward cap deformation

5.1 Geometric deformations

Fig. 9 shows the various distributions of relative web deflections with load for square spar and modified spar which are considered in the present work and it compared with Jensen *et al.* (2006) at leading and trailing edges. It is observed that calculated web deflection at leading and trailing edges are in good agreement with the experimental work for square shape spar. It is also found that web deflection for combined shape (box and cross) at root segment is less in comparison to both square shape spar and experimental. Fig. 10 shows the cap deformation at transition segment with load it is found that the relative cap deflection increases with increasing load. It is also observed that the cap deflection for combined spar is in good agreement with experimental while the cap deflection for square spar is more than experimental and shows reasonable accuracy.

5.2 Influence of shape of spar

Figs. 9 and 10 represents the differences in deflection of cap and web. It is clear that the deflection for the combined spar is less than the square shape spar. For reducing the deflection of cap and web the spar used in the blade is of combined shape (box and cross).

6. Conclusions

In this work, a horizontal axis wind turbine blade is designed with the help of Glauert's optimal rotor theory. A computer program is developed for evaluation of the chord, thickness and twist distribution by considering the lift coefficient constant along the blade. Blade is modeled in ANSYS 12.0 with airfoil NACA 63_4–221. Two different type of spar are used for the analysis of blade which are square spar and combined shape (box and cross). Web deflection and cap deflection has been calculated at root and transition segment. It is observed that calculated web deflection at leading and trailing edges are in good agreement with the experimental work for square shape spar. It is also found that web deflection for combined shape (box and cross) at root segment is less in comparison to both square shape spar and experimental. It is found that the relative cap deflection increases with increasing load. It is also observed that the cap deflection for combined spar is in good agreement with experimental, while it shows reasonable accuracy with experimental for square spar. It is clear that the deflection for the combined spar is less than the square shape spar. Nevertheless, a deep experimental validation of this computational approach is strictly needed. It requires a very complex experimental setup, which is difficult to manufacture. Hence, through this analysis it can be prescribed that a new shape of spar of combined shape (box and cross) could be more useful for increasing the strength of blade.

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