IOP Conf. Series: Materials Science and Engineering **241** (2017) 012015 doi:10.1088/1757-899X/241/1/012015

Stress analysis of composite wind turbine blade by finite element method

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Abstract. In this study, the finite element analysis software ANSYS was used to analyze the composite wind turbine blade. The wind turbine blade model used is adopted from the 5 MW model of US National Renewable Energy Laboratory (NREL). The wind turbine blade is a sandwich structure, comprising outermost carbon fiber cloth/epoxy composites, the inner glass fiber/vinylester layers, and PVC foam core, together with stiffeners. The wind pressure is converted into the load on the blade structure. The stress distribution and deformation of wind turbine blade were obtained by considering different pitch angles and at different angular positions. The Tsai-Hill criterion was used to determine the failure of wind turbine blade. The results show that at the 0^o pitch angle, the wind turbine blade is subjected to the largest combined load and therefore the stress is the largest; with the increasing pitch angle, the load gradually decreases and the stress is also smaller. The stress and displacement are the greatest when the wind blade is located at 120^o angular position from its highest vertex.

1. Introduction

In recent years, the wind power industry is booming, the wind turbine market has also been expanding. Most of the wind turbine blades are made of composite materials, which with light weight can effectively enhance the structural strength and general performance for wind power generation. Daniel and Abot [1] used three-point and four-point bending tests to obtain the bending behavior of sandwich composite beams and found that since the Young's modulus of the core material was much smaller than that of the surface material, the influence of the core material was negligible. Kim and Swanson [2] performed the experiment for the carbon fiber/epoxy composite sandwich beam structure and found that when the core density was small, the failure resulted from shear damage of the core material; when the core was thicker with high density, the failure came from the fiber fracture of surface layers. Steevens and Flect [3] found that from three-point bending test, the foam core could be used for relatively lower load applied on the sandwich structure. Duan and Zhao [4] used the finite element method to analyze the stress distribution of a 600 kW wind turbine blade and found that the maximum stress occurred at the root of wind blade. Yeh et al. [5] evaluated the stress distribution and deflection of NREL 5MW wind blade with different structural stiffeners.

In this study, the stress and deformation analyses of the NREL 5MW wind blade with different pitch angles, 0^o, 5^o, 15^o at different angular positions under wind load were carried out by finite element analysis. The wind turbine blade, comprising outermost carbon fiber cloth/epoxy composites, the inner glass fiber/vinylester layers, and PVC foam core, is a sandwich structure. The Tsai-Hill failure criterion was used to determine the failure of wind blade.

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2. Finite element analysis

The finite element analysis software ANSYS was used to analyze the stress distribution and deformation of the wind turbine blades under the wind load.

2.1 Wind turbine blade

The wind turbine blade model is adopted from the 5 MW model of US National Renewable Energy Laboratory (NREL). The model has a length of 61.5 m, using 19 airfoil sections. The circular part connecting the hub is 6.83 m long, 14% of total length; the remaining part uses DU99W405, DU99W350, DU97W300, DU91W2250, DU93W210, and NACA64-618 airfoils [6]. The longest chord length is 4.652 m, located at position about 23% of total length [7]. Two vertical stiffeners are placed inside the wind blade to improve the blade strength, as shown in Figure 1. The outer carbon fiber cloth/epoxy, the inner glass fiber/vinylester composites, and PVC foam core were adopted as the blade material to form a sandwich structure. The material parameters are referred to Yeh et al. [5]. The carbon fiber cloth/epoxy composites has total of 20 layers including both upper and lower parts. The glass fiber/vinylester composites has stacking sequence, $[0_n/\pm 45_n/90_n]_s$, to make a minimum of 16 layers and a maximum of 80 layers including both upper and lower parts. The single layer thickness for both materials is 0.28 mm, together with central PVC foam to form a sandwich structure in the wind blade. Figure 2 shows the thickness variation of the three materials in the sandwiched wind blade.

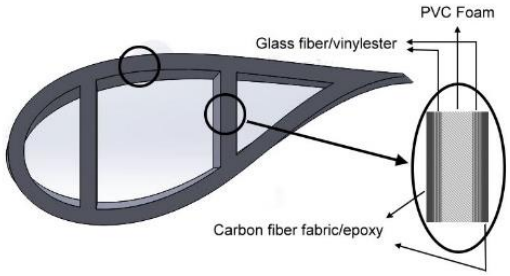


Figure 1 Stiffened wind turbine blade

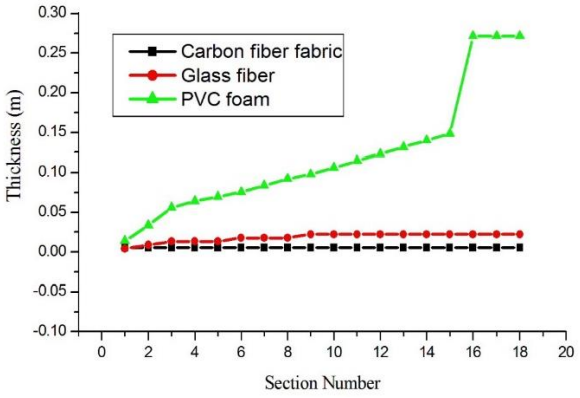


Figure 2 Thickness variation in wind blade

2.2 Analysis model of wind turbine blade

The ANSYS software was used to analyze the deformation and stress distribution of the wind turbine blade. Mesh convergence was carried out for the element number from 7000 to 60000 and the optimal model was obtained when the blade model reaches more than 25000 elements, as shown in Figure 3, and the maximum von Mises stress approaches a convergent value. In this study, the clockwise rotation speed of the wind blade was set at 12.1 rpm, which corresponding to the maximum designed wind speed of 25 m/s. The three cases analyzed were for three pitch angles 0°, 5°, 15° of wind blade. The wind blade was subjected to the gravity, the wind load, and centrifugal force. Figure 4 shows various load and boundary conditions for the wind blade at the vertical position and the gravity force is acting through the wind blade from its tip to the root end. The root end of the wind blade is fixed on the wind turbine hub, so the petiole degrees of freedom are all fixed.

3. Results and discussion

The stress analysis results of NREL 5MW wind turbine blade by finite element software ANSYS were obtained. The stress distribution and deformation of three angular positions and four pitch angles of wind blade on are discussed.

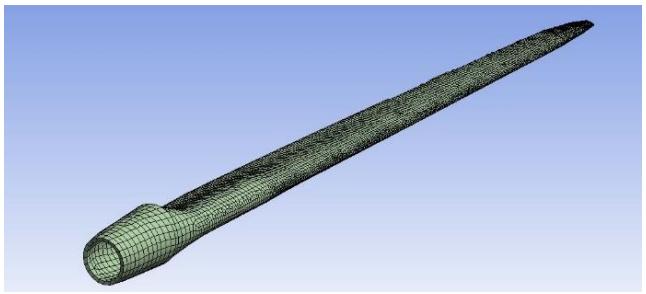


Figure 3 Finite element model of wind turbine blade

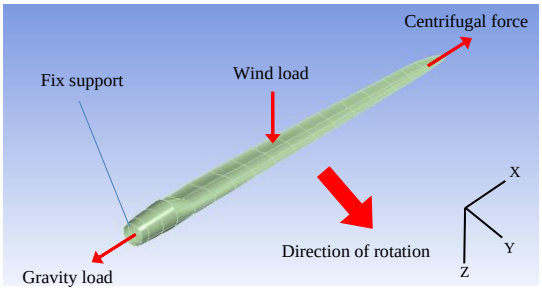
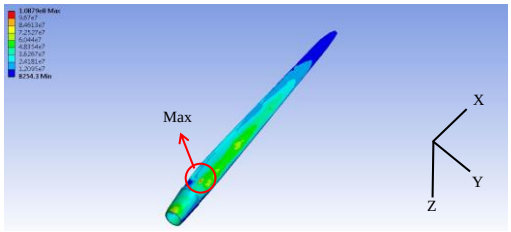


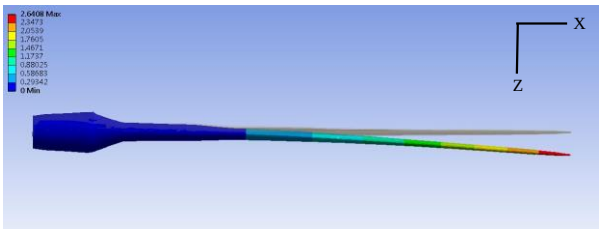
Figure 4 Load on wind turbine blade

3.1 Different angular position

The wind turbine blade under wind load at three angular positions is investigated. With the pitch angle $0^{\mathbf{o}}$, the wind blade is subjected to a maximum wind pressure load to bend the blade structure. The maximum stress occurs at the junction of circular airfoil and DU99W405 airfoil near the stiffener edge, where the blade shape changes a lot. When the wind blade is located at vertical position, the maximum von Mises stress value is 86.11 MPa. When the blade is at $120^{\mathbf{o}}$ counterclockwise angular position from its highest vertex, the combination of the wind load, the gravity and the centrifugal force resulted in a maximum von Mises stress of 72.95 MPa at the junction of the circular airfoil and DU 99W405 airfoil near the stiffener edge. When the wind blade is at $120^{\mathbf{o}}$ clockwise angular position from its highest vertex, the load on the blade is added by the wind load, the gravity and the centrifugal force and resulted in a maximum value of von Mises stress 108.79 MPa at the junction of the circular airfoil and DU99W405 airfoil near the stiffener edge.

Figure 5 shows the stress distribution and the deformation of the wind blade at $120^{\mathbf{o}}$ clockwise angular position. The maximum tip displacements at three positions are 2.55 m, 2.27 m and 2.54 m, respectively. The deflection of wind blade is similar to that of a cantilever beam as shown in Figure 5(b), in the flapwise direction of wind blade. The maximum von Mises stresses and maximum tip displacements of NREL 5MW wind turbine blade at different angular position are shown in Table 1.





(a) von Mises stress distribution (b) Deflection of wind blade

Figure 5 Results of NREL 5MW wind blade at 120° clockwise angular position

Table 1 Results of wind blade at different angular positions and for different pitch angles

Item	Blade angular position			Pitch angle		
	Vertical	-120^{o}	120^{o}	0^{o}	5^{o}	15^{o}
$\sigma_{vM,max}$ (MPa)	86.11	72.95	108.79	108.79	69.10	60.92
Tip disp.(m)	2.55	2.27	2.64	2.64	2.38	2.12

3.2 Different pitch angle

This section explores the results of three different pitch angles at 0^{o}, 5^{o}, and 15^{o} for wind blade. The results of the wind blade with 0^{o} pitch angle are described in the previous section for different angular position; the results of the wind blades with 5^{o} and 15^{o} pitch angles, with decreasing wind load, the smaller maximum stresses are all located at the junction of the circular airfoil and DU99W405 airfoil near the stiffener edge, same as those in the wind blade with 0^{o} pitch angle. For the wind blade with larger pitch angle 15^{o}, the values of von Mises stress and tip displacement are smaller than the case with pitch angles 0^{o} and 5^{o}. The maximum von Mises stress values for the wind blade with pitch angle

5^o and 15^o were 69.1 MPa and 60.92 MPa, respectively. The simulated maximum von Mises stresses and maximum tip displacements of NREL 5MW wind turbine blade at different pitch angle are shown in Table 1.

3.3 Failure criterion of wind blade

The Tsai-Hill failure criterion was used to determine the failure of wind blade. The maximum von Mises cases, at 120^o clockwise angular position in Table 1, are summarized in Table 2 for different pitch angles. It can be seen from Table 2, for the wind blade with pitch angle 0^o, the glass fiber/vinylester composite layers fails for fiber orientation 45^o and 90^o. Reinforcements are needed for the wind blade with pitch angle 0^o and increasing the pitch angle is an alternative way to prevent the wind blade from failure.

Table 2 Simulated results by Tsai Hill failure criteria

Material	Fiber orientation	Pitch angle		
		0^o	5^o	15°
Carbon fiber fabric/epoxy	0°/90°	0.447	0.568	0.235
Glass fiber/vinylester	0°	0.470	0.723	0.281
	45°	1.435	0.106	0.254
	90°	1.611	0.639	0.530

4. Conclusions

In this study, the stress distribution and deformation of the NREL 5MW wind turbine blade under various loads was analyzed using finite element analysis software ANSYS. The results for wind turbine blade with different angular position and different pitch angle are discussed. For the wind blade with 0^o pitch angle, the combined load on the wind blade is a maximum. With increasing pitch angle, the load on the wind blade is decreasing at a specified angular position. When the blade is located at 120^o clockwise angular position, maximum von Mises stress occurs at the junction of the circular airfoil and DU99W405 airfoil near the stiffener edge, resulted from the combined load by the wind load, the gravity and the centrifugal force. The use of stiffener improves the rigidity of the blade to resist the bending moment of the blade, and also bears the combined load of wind blade. Increasing the pitch angle can reduce the stresses in the wind blade and can prevent the wind blade from failure.

Acknowledgements

The authors would like to thank the support by Ministry of Science and Technology, Taiwan, ROC, under the Grant MOST 105-2221-E-007-031-MY3. The support is greatly acknowledged.

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