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Study on Structural Optimum Design of Composite Lamination for Some 1.2 MW Wind Turbine Blade

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Abstract: Performance of wind turbine blade varies with changes of lamination parameter. Lay-up design and verified analysis of stiffness and strength are the very important work in the design of large scale composite wind turbine blade. According to theoretical calculating result of stress, six different lay-up structures of 1.2 MW horizontal axis wind turbine blade, which can effectively endure various loads, are designed primarily. Based on composite laminate theory and finite element method, through analyzing their stress-strain, the optimal lay-up schema is confirmed. The verified analysis of stiffness and strength were performed under extreme load conditions. Numerical analysis results show that the designed blade structure was safe and the value of stress and strain was low.

Key words: Composite lamination, lay-up optimum, structural analysis, wind turbine blade

INTRODUCTION

As the renewable, green and environmental protection energy, wind energy resource is one of the most developing hi-technologies in energy field. The blades of wind turbine rotor are regarded as the most critical component of the wind turbine system. Because of its special functions, such as high specific stiffness and specific strength, better designability, high performance of antifatigue and antifailure, easy integral molding of large-area and wonderful corrosion resistance, reinforced composite material is widely applied in large scale wind turbine blades. With the development to large power, light weight and high performance ratio, large scale wind turbine blades is basically made of reinforced material and thermosetting base-resin and produced through lay-up process at present (Shirinzadeh *et al*., 2004).

Pan *et al*. (2012) study the composite ply strength properties of a wind turbine blade root based on composite material finite element method and Tsai-Wu strength criterion. Lin and Lee (2004) study the stacking sequence optimization of laminated composite structures using finite element method and genetic algorithm. Li and Chen (2009) has performed structural dynamics and statics analysis of some blade with finite element method and finished the optimum design on the basis of analysis through changing lamination lamination schema. Wang and Guo (2006) study structural optimization of composite using the fiber orientation and the lamina thickness as the design variables and the last-ply failure load as the objective.

Motion and stress status of wind turbine blade is very complicated. In order to improve its performance, quality and fatigue life, it is necessary to design different lay-up structures according to calculating results and experience in blade design stage. Through stress-strain analysis of different structures, the optimal lay-up schema can be determined and the verified analysis of stiffness and strength can be performed under extreme load conditions.

MW WIND TURBINE BLADE

Design power of wind generating set is 1.2 MW, rated rotational speed is 20 rpm, rated wind speed is 13 m s^{-1}, maximum tip ratio of transmission is 7.6, blade number is 3 and blade length is 30 m. NACA 64-618 airfoil was used at the blade tip to keep good aerodynamic performance and DU and EU airfoil were used at the blade root for good structural performance. Figure 1 shows the NACA 64-618 aerofoil outline.

The profile of 1.2 MW wind turbine blade was designed based on BEM theory and modified Wilson algorithm. Through correcting the airfoil from structure and processing point, the relative thickness distribution of the blade wing is shown as in Fig. 2.

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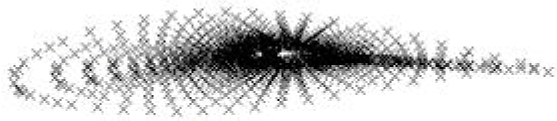

Fig. 1: NACA64-618 airfoil point cloud

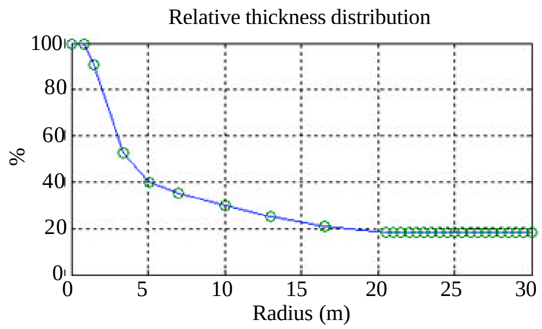

Fig. 2: Relative thickness distribution of wing

PRIMARY DESIGN OF BLADE LAY-UP STRUCTURES

Blade mainly endures tension and compression stress, bending stress and distorting stress produced by aerodynamical, centrifugal and gravitational loads in its operating process. The skin-spar-foam sandwich structure was used to minimize the blade weight and to get the structural stability against buckling and vibration. The blade can be regarded approximately as one-way bearing component. Because the maximum stress generates on blade root and stress gradually reduces along blade length, the maximum lay-up thickness should locate in the blade root (Berry and Lockard, 2002; Kong *et al*., 2005). Table 1 presents the designed laminate thickness of blade. The thickness of blade root is 80 mm and the thickness of blade tip is 20 mm. From root to tip, the thickness of blade sequentially reduces.

According to curved face form, performance requirement, magnitude and direction of load under working condition, composite lay-up design of wind turbine blade mainly determines lay-up angle, lay-up thickness and lay-up sequence. Design must be satisfied the main technological demands of resisting ultimate loads, deflection in the permissible range and avoiding resonance (Bao, 2007).

Table 1: Blade design thickness of different cross-sections

Order No. of cross-section	1	2	3	4	5	6	7
Position of cross-section (m)	0.0	0.85	5.1	7.5	10	12.5	13
Thickness of laminate (mm)	80.0	75.00	70.0	65.0	60	60.0	55
Order No. of cross-section	8.0	9.00	10.0	11.0	12	13.0	14
Position of crosssection (m)	15.0	17.50	20.0	22.5	25	27.5	30
Thickness of laminate (mm)	50.0	45.00	40.0	35.0	30	25.0	20

Based on composite laminate theory, design structures of different laminates can be determined primarily according to loading characteristic and stress relationship of composite blade. Through calculating stress relationship of different cross-sections, the main ratio between positive stress and shear stress have 5:1, 7:1 and 9:1. When the ratio is 7:1 and 9:1, action of shear stress is little. Placing 0 and 90° fiber resists bending and placing 15 and 30° fiber resists shearing and bending in Y direction. When the ratio is 5:1, placing 0 and 90° fiber resists bending and 45° fiber resists shearing. Therefore, six different kinds of fiber lay-up schemes are obtained. They are $(\pm45/0°)_S$, $(0/90°)_S$, $(0°/\pm45°/90°)_S$, $(0°/\pm15°/90°)_S$, $(0°/\pm30°/90°)_S$ and $(0°/\pm60°/90°)_S$.

STRUCTURAL ANALYSIS OF DIFFERENT LAY-UP

Static numerical simulation of wind turbine blade is to analyze and study its stress and strain of different lay-up structures. and then to determine the optimal lay-up schema aimed the maximum structure strength and stiffness as final goal.

To finite element analysis of composite lay-up structure, different laminations adopt different element types and attributes. Because of the random orthogonal aeolotropism of GRP mechanical performance, material performance relates to its main arbor orientation, lay-up number and lay-up thickness. Special layer elements is used to simulate composite and composite parameters of the blade, such as lay-up angle, lay-up number and lay-up thickness can be set. The boundary condition of finite model is to fix the blade root fully, to act wind pressure on the blade out-surface and to act weight and centrifugal loads on calculating model. When blade is rotating, its stress changes with rotating position. The extreme stress is calculated in the extreme wind speed 60 m sec^{-1} and 0° dangerous position which bears the maximum stress.

Figure 3 show the Von Mises equivalent stress analysis results of six lay-up structures.

Table 2 presents the Von Mises equivalent stress analysis results of six lay-up cases under extreme loads.

According to the results of this analysis, the maximum equivalent stress is generated on blade root under extreme loads and it is caused by centrifugal load. The maximum equivalent stress occurs in $(\pm45°/0°)_S$ and the minimal one occurs in $(0°/\pm60°/90°)_S$.

Table 2: Von Mises equivalent stress analysis results

No.	Lay-up sequence	Von Mises equivalent stress (Mpa)
1	$(\pm45°/0°)_S$	5.83
2	$(0°/90°)_S$	4.91
3	$(0°/\pm45°/90°)_S$	3.91
4	$(0°/\pm15°/90°)_S$	4.26
5	$(0°/\pm30°/90°)_S$	4.06
6	$(0°/\pm60°/90°)_S$	3.85

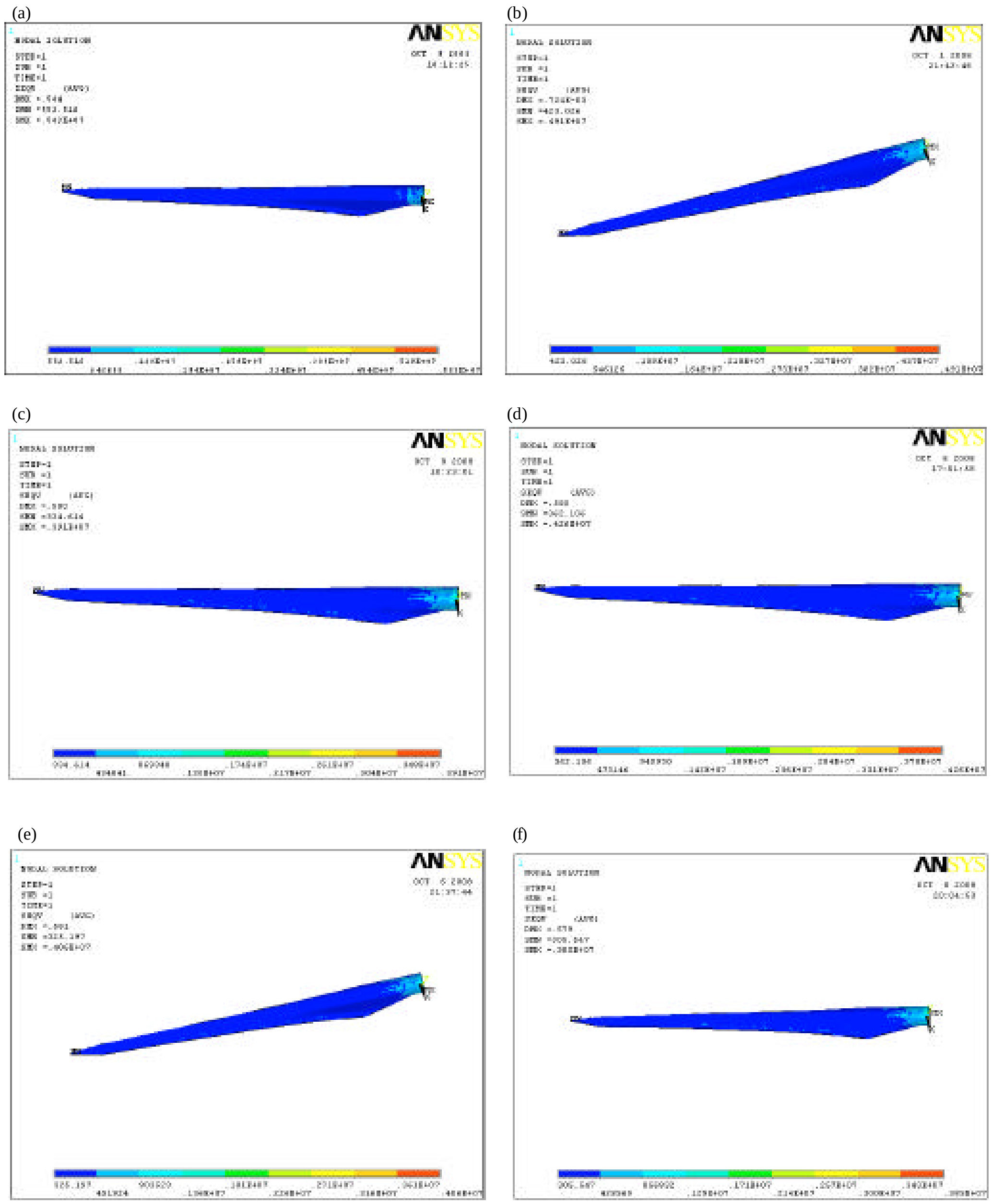

Fig. 3(a-f): Von mises equivalent stress of six lay-up structures, (a) Lay-up structures of $(\pm45°/0°)_S$, (b) Lay-up structures of $(0°/90°)_S$, (c) Lay-up structures of $(0°/\pm45°/90°)_S$, (d) Lay-up structures of $(0°/\pm15°/90°)_S$, (e) Lay-up structures of $(0°/\pm30°/90°)_S$ and (f) Lay-up structures of $(0°/\pm60°/90°)_S$

Table 3: Displacement and deflection for different lay-ups

No.	Lay-up sequence	Displacement of blade tip (m)	Deflection of blade tip (%)
1	$(\pm45°/0°)_S$	0.837	2.79
2	$(0°/90°)_S$	0.809	2.70
3	$(0°/\pm45°/90°)_S$	0.658	2.19
4	$(0°/\pm15°/90°)_S$	0.724	2.41
5	$(0°/\pm30°/90°)_S$	0.703	2.34
6	$(0°/\pm60°/90°)_S$	0.580	1.94

Table 3 presents the maximum placement and tip deflection results under extreme loads.

Figure 4 shows the total deformation of six lay-up structures.

According to the results of this analysis, the maximum placement of blade is generated on the blade tip and it is caused by wind pressure.

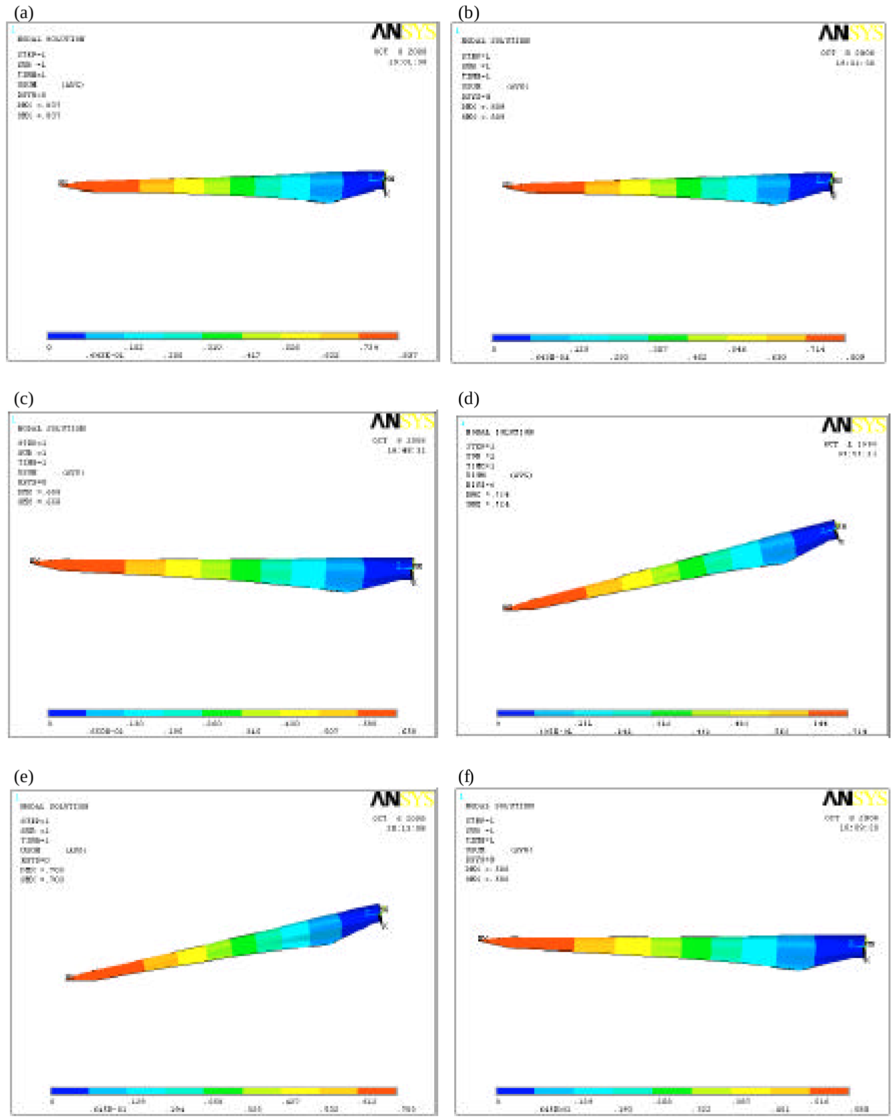

Fig. 4(a-f): Total deformation of six lay-up structures, (a) Lay-up structures of $(\pm45°/0°)_S$, (b) Lay-up structures of $(0°/90°)_S$, (c) Lay-up structures of $(0°/\pm45°/90°)_S$, (d) Lay-up structures of $(0°/\pm15°/90°)_S$, (e) Lay-up structures of $(0°/\pm30°/90°)_S$ and (f) Lay-up structures of $(0°/\pm60°/90°)_S$

The maximum placement occurs in $(\pm45°/0°)_S$ and the minimal one occurs in $(0°/\pm60°/90°)_S$.

DETERMINING THE OPTIMAL LAY-UP DESIGN AND VERIFYING ITS STRENGTH AND STIFFNESS

Through comparing the Von Mises stress and tip placement of six lay-up schemes, the $(0°/\pm60°/90°)_S$ is the optimal lay-up structure. Figure 5 present the placement analysis results of some cross-sections.

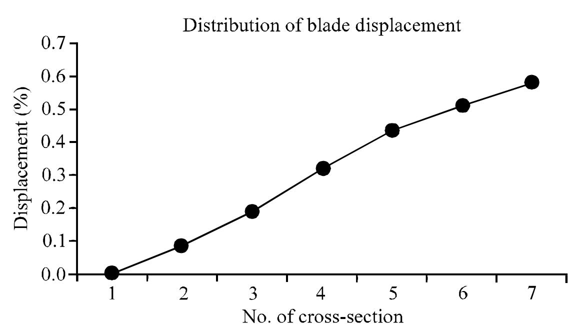

Fig. 5: Displacement distribution curve of the blade

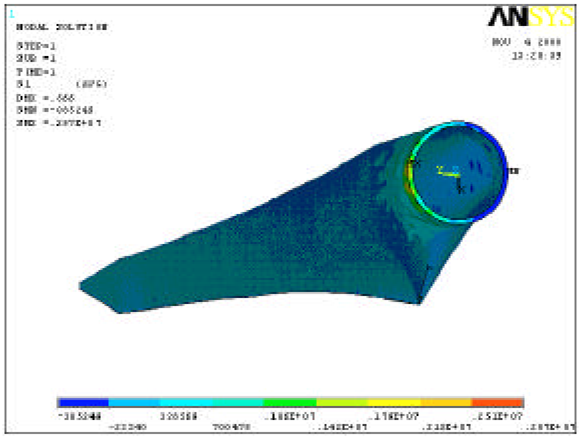

Fig. 6: First principle stress of the blade

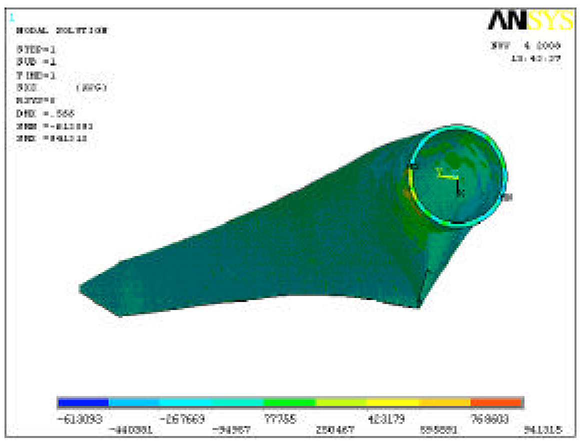

Fig. 7: XY shear stress of the blade

The curve of placement distribution is approximately linear. The maximum placement is 0.580 m and on the tip part. The maximum deflection is 1.93% of the whole blade length and it satisfied the design stiffness demand.

Strength of composite materials relates to its performance and stress-strain status and strain energy after loading. At present, macromechanics strength theory and micromechanics strength theory are the main strength theory of composite materials. Strength theory of macromechanics has developed relative mature stage. Maximum stress criterion and maximum strain criterion based on macroscopic damage criterion are the best macroscopic strength theory to analyze strength problem of composite materials (Wang *et al.*, 2006; Huang and Zhang, 2007). Because of its high precision and wide application, the maximum stress criterion is adopted in this study. It demands that every stress must be less than their ultimate strength. Otherwise the blade will be failure.

Strength analysis under extreme loads is shown as in Fig. 6 and 7.

According to the results of this analysis, the maximum first principal stress occurs on the blade root and it is 2.87 Mpa. Allowable stress was 28.99 Mpa. The maximum shearing stress occurs on the blade root too and it is 0.941 Mpa. Allowable shearing stress was 11.63 Mpa. Since the safety factor for the allowable stresses was 5.0, which was calculated from the allowable stress and the predicted stress, the designed wind turbine blade satisfied the design strength demand.

CONCLUSION

Lay-up design and verified analysis of stiffness and strength are the very important work in the design of large scale composite wind turbine blade. An E-glass/epoxy composite blade for a 1.2 MW HAWTS was designed and analyzed in this study. According to stress calculating results and experience, six different kinds of fiber lay-up schemes are designed. Aimed the maximum structure strength and stiffness as final goal, through stress-strain analysis of different structures, the optimal lay-up schema $(0°/\pm60°/90°)_S$ was determined. The verified analysis of stiffness and strength of the optimal lay-up schema is performed under extreme load conditions. Numerical calculation shows that the curve of placement distribution is approximately linear and the maximum deflection of the blade tip satisfied the design stiffness demand. The maximum stress criterion is adopted and the maximum first principal stress and shearing stress of the blade root both satisfy the design strength demand.

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REFERENCES

Bao, H.B., 2007. Stress and model analysis of compound blade under wind pressure and centrifugal load. Power Syst. Eng., 23: 68-69.

Berry, S. and S. Lockard, 2002. Parametric study for large wind turbine blades. SAND 2002-2519, Unlimited Release Printed.

Huang, Z.M. and H.S. Zhang, 2007. Current status and future trend of researches on the strength of fiber-reinforced composites-a summary of the results from a failure olympics. Adv. Mech., 35: 80-98.

Kong, C., J. Bang and Y. Sugiyama, 2005. Structural investigation of composite wind turbine blade considering various load cases and fatigue life. Energy, 30: 2101-2114.

Li, C.L. and C. Chen, 2009. Structural analysis and lamination optimum design of wind turbine rotor blade. FRP/CM, 6: 50-53, (In Chinese).

Lin, C.C. and Y.J. Lee, 2004. Stacking sequence optimization of laminated composite structures using genetic algorithm with local improvement. Comput. Struct., 63: 339-345.

Pan, B.S., S.J. Xie and L.H. Liang, 2012. Research of composite PLY strength properties for the root of wind turbine blade. ACTA Energiae Solaris Sinica, 5: 769-774.

Shirinzadeh, B., G. Alici, C.W. Foong and G. Assidy, 2004. Fabrication process of open surfaces by robotic fibre placement. Robotics Comput. Integrated Manuf., 10: 289-294.

Wang, B.L., S.P. Wu and J. Liang, 2006. Strength theory and failure analysis of composite materials. Fail. Anal. Prevent., 2: 13-19.

Wang, X.Y. and B. Guo, 2006. Optimization of laminated composite plates based on the last-ply failure criterion. J. Wuhan Univ. Technol., 1: 140-143.