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Single Parameter Sensitivity Analysis of Ply Parameters on Structural Performance of Wind Turbine Blade

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Abstract: The various ply parameters of composite wind turbine blade have crucial influence, of respectively varying degree, on the static strength and stiffness of the blade, elements closely related to its performance. In this article, the method of the single-parameter sensitivity analysis is presented. A 1.5 MW wind turbine blade is considered as the study object, where the load of the blade is calculated and the respective finite element model is established. According to engineering practice, the investigation range of ply parameters is determined, and the test design scheme of ply parameter for the blade is constructed. The Tsai-Wu failure factor and the maximum displacement for various ply parameters combinations are calculated, and the empirical mathematical models between blade performance and ply parameters are established using polynomial regression analysis method. Furthermore, the sensitivity functions between ply angle, biaxial ply thickness ratio and the blade's static strength and stiffness are established using the single-parameter sensitivity method, and the sensitivity of key parameters on the blade performance is investigated. Finally, the authors provide the changing rule of ply parameter to blade performance and the optimized value for ply angle and biaxial fabric ply thickness ratio. These calculations constitute the method and technology support for the design and optimization of the blade ply structure.

Keywords: Ply parameters; sensitivity analysis; structural performance; mathematical models; wind turbines blade

1 Introduction

Composite materials present many favorable characteristics, including superior strength to density ratio, large specific stiffness, good fatigue wear resistance and corrosion resistance, light weight, structure design flexibility and easy whole forming. Owing to these features, they are widely used in main structure parts of aerospace industry and wind power, such as aircraft wing, shell and nozzle of solid rocket motor, wind turbine blade etc. As more composite based products appear, the focus on product quality increases [1,2]. In the case of wind turbines, the blades, as the critical component of capturing the wind energy, are subject to complex loading conditions. The normal operation of a wind turbine is assured by factors, such as optimized design, excellent performance and reliable blade quality. Three key parameters in the layering process for a blade are ply angle, ply thickness and ply stacking sequence. Parameters of composite placement produce significant effects on the strength and stiffness of construction, closely related to blade performance [3]. Modern wind turbine blades are complex composite structures, whose forming process is multi-parametric and multi-objective. A wide area of existing research and engineering practices has demonstrated that different combinations of ply parameters influence blade performance on a varying degree.

In the last few decades, a large number of studies have been devoted to optimization and sensitivity analysis of the wind turbine blade. Sjølund et al. [4] minimized the mass of the wind turbine blade with fixed outer geometry, based on structural gradient sizing optimization while considering manufacturing constraints, tip displacement, buckling and static strength criteria. In the work of Sørensen et al. [5], topology and thickness optimization of laminated composites, while considering manufacturing constraints, were studied to provide reduced risk of failure due to delamination and matrix cracking problems. Veludurthi et al. [6] studied modal and harmonic analysis of sandwich structure typed composite wind turbine blades, fabricated from GFRP and epoxy. The forced vibration approach was used to analyze the responses of the blade at different forces and frequencies, which provided a feasible study, defining the effective blade structure. The mathematical models, describing the relation between ply parameters, Tsai-Wu failure factor and maximum displacement of blade, were established by multivariate linear regression method, while the influence of ply parameters on the blade structure performance was analyzed in the work of Wu et al. [7]. Through the optimization of several combinations of both the type and the lay-up of the laminas, based on a multi-objective genetic algorithm, Monte et al. [8] improved the wind turbine blade without changing the composite materials adopted to the original architecture. The overall blade weight was reduced significantly and its flap-wise rigidity was increased correspondingly. Chen et al. [9] established a finite element parametric model for a 2 MW wind turbine blade and optimized composite structures of the blade by combining principles of finite element analysis and particle swarm algorithm. In order to improve wind energy harvesting, Ayoub et al. [10] analyzed, theoretically and experimentally, offshore wind turbines. The energy produced was calculated at different wind speeds, and curves that show the power extraction from experimental study and theoretical calculations are generated. Gao et al. [11] analyzed parameter sensitivities affecting the flutter speed of a 5 MW horizontal axis wind turbine blade, and obtained the time domain aeroelastic response of the wind turbine blade section, according to the Runge-Kutta method. Chen et al. [12] proposed a sensitivity-analysis-based wind turbine optimization strategy. Through controlling proportionally blade pitch and generator torque to the generator speed tracking error, the wind turbine performance can be evaluated with control variables sensitivities directly. Riccardo et al. [13] simulated the post-stall behavior of wind turbine blade at high Reynolds number based on CFD scale-resolving methods, and assessed the influence of time integration duration, grid span-wise resolution and domain width, on the accuracy of the simulations, through exhaustive sensitivity analysis. Based on single-factor analysis, Zhang et al. [14] used range and variance analysis to study the sensitivity of four operating parameters to the thermodynamic performance of an oxyfuel combustion power generation system. However, this method relies heavily on orthogonal design, and cannot be used in regression analysis. In the work of Shi et al. [15], an integrated methodology, combining Multi-parameter Sensitivity Analysis (GMSA) and Local Single-parameter Sensitivity Analysis (LSSA), was presented to obtain the optimal intervals. The GMSA method was used to investigate the sensitivity of each parameter, while the LSSA method was applied to calculate the sensitivity of a single parameter within the corresponding range. The process parameters range was optimized, and the comprehensive optimized intervals of the winding parameters were established. The focus of this research is on the composite tape winding product, which is a revolving body of equal thickness, and the process parameters are continuous variables. However, the wind turbine blade is a non-revolving body of varying thickness and the ply stacking sequence is a discrete variable. There are significant differences between the wind turbine blade and a regular revolving body construction.

It becomes evident that prior research work is lacking in sensitivity analysis on ply parameters of a wind turbine blade. The question worth considering is how to identify the influence degree of ply parameters on blade performance and thus select an optimal configuration of these parameters, significantly improving the quality of the blade performance.

The focal point of the current study lies in the fact that the sensitivity analysis method can provide the basis for ply parameters selection and serve to improve the strength and stiffness of wind turbine blade. More specifically, the contributions of this paper include: (1) a proposed method of single-parameter sensitivity analysis for key ply parameters; (2) an empirical model relating blade performance to ply parameters, established in terms of simulation data; (3) a single-parameter and comprehensive sensitivity analysis of ply angle and biaxial fabric ply thickness ratio on the Tsai-Wu failure factor and the maximum displacement of blade; (4) determining the changing rule of ply parameters to blade performance.

2 The Forming Process and Modeling of Wind Turbine Blade

As depicted in Fig. 1, the mainstream mega watt-size blade generally adopts the structure of a main beam, double web, internal and external skins. The beam mainly bears most bending loads. The skin maintains the aerodynamic shape and bears most shear loads, while the web is mainly under shear stress [16].

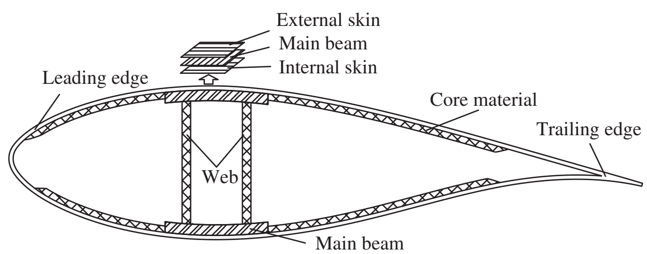

Figure 1: Structure of mega watt-size blade

Since the wind turbine blade is a non-revolving body with a cover of varying thickness, it is comprised of composite material formed by lay-up and resin impregnation process. This mainly includes composite cloth laying, resin vacuum pouring and curing, mold closing and mold stripping (Fig. 2).

The 1.5 MW wind turbine blade, used in the experiment, is a typical type of blade, which adapts to the IEC IIIA wind field level and uses a modified airfoil of Aerodyn and NACA 63. The blade length is 40.25 m and the diameter of the wind wheel is 82.5 m. The maximum string length is 3.183 m and the rated rotational speed is 17.4 rpm.

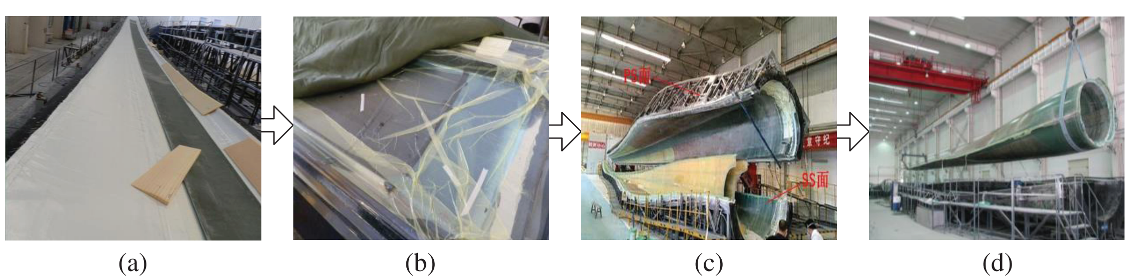

Figure 2: The main forming process of wind turbine blade. (a) Laying of composite cloth for blade skin. (b) Resin vacuum pouring and curing. (c) Mold closing. (d) Mold stripping

Glass fiber fabric, soft Sandwich material and epoxy resin were used in this blade. The glass fiber fabric includes uniaxial fabric UD1250 (0°/90°), biaxial fabric EKB808 (+45°, −45°) and three-axial fabric EKT1215 (+45°, 0°, –45°/+45°, 90°, −45°). The soft Sandwich material is balsa wood, while the matrix is made of epoxy resin 2511-1A.

The blade is divided into three parts: the anterior segment, the middle segment and the root segment along its span direction. As the blade bears sustained load during operation, the middle segment, covering the 1/3 to 2/3 blade length, starting from the blade root, must meet the requirement of enough strength and stiffness. Blade root is the region where the blade bears the maximum load. Since most of the load on the blade is concentrated along the root and middle part, the length range 0–28.2 m away from the blade root is used as the study object.

Because of their large size, extreme complexity, high cost and time-requirements, it is practically difficult to do tests on the actual wind turbine blades. Currently, the analysis methods used universally are relatively common, with finite element analysis in numerical methods being generally used to study stiffness, strength, stability and fatigue of wind turbine blades [17]. The calculations results of finite element method for wind turbine blade are approved by the Certification Specification of Wind Turbines 2010 [18].

The GH-Bladed software is used to simulate the wind field, and the wind condition is simulated as load applied to the blade. The load includes the concentrated force load and bending moment load in three-dimensional coordinates directions on a variety of sections of the blade. The calculated loads of 15 sections of blade, under DLC1.5g-2 limit working condition, are summarized in Tab. 1.The section position is the distance from blade root to section.

Table 1: Sectional loads of DCL1.5 g-2 limit working condition

Section position	Concentrated force load (kN)			Bending moment load (kN·m)		
	F_x	F_y	F_z	M_x	M_y	M_Z
0.7 m	0.2	0.0	7.9	141.3	33.7	0.0
1.4 m	0.2	0.1	7.9	141.3	33.7	0.0
1.8 m	1.1	2.2	2.3	80.9	19.3	0.0
3.2 m	12.2	4.0	6.1	281.7	189.8	15.2
4.2 m	0.6	2.6	4.2	197.5	60.9	0.6
6.5 m	6.4	10.8	8.0	380.8	282.2	11.2
8.5 m	4.8	12.7	7.1	359.7	105.3	0.5
11.2 m	9.9	23.4	9.3	486.1	135.3	0.3
14.6 m	10.4	26.2	8.7	465.3	117.5	0.2
16.7 m	4.8	14.0	4.6	246.1	57.0	0.5
18.5 m	3.3	10.9	3.1	188.3	41.6	0.8
22.2 m	5.6	25.7	5.0	304.4	53.0	0.4
23.1 m	1.1	0.3	1.0	64.4	13.7	0.6
25.7 m	3.1	10.0	2.5	170.3	34.6	1.8
28.2 m	2.1	11.4	2.3	137.0	14.6	0.3

The blade modelling process is as follows:

(1) Processing data of discrete points on the blade airfoil, the spatial coordinates are collected.

(2) Using cubic B-spline fitting method, two spline curves are plotted with leading and trailing edge points of all section airfoils. Using free-form surface modeling function of the UG NX software, the shell model of the blade is obtained by sweeping the two curves as guiding lines.

(3) According to the actual laying scheme, material properties are attributed layer by layer. Six degrees of freedom at blade root are totally restrained, and the QUAD4 SHELL element is used for meshing. Considering different section sizes at each blade section, sectional loads are applied at the center of each section. A finite element model of 1.5 MW blade is plotted as illustrated in Fig. 3, consisting of 132,781 elements and 65,772 nodes.

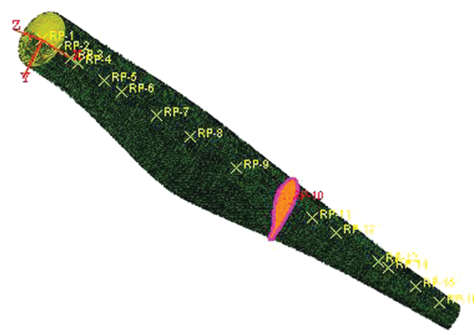

Figure 3: Finite element model of 1.5 MW wind turbine blade

3 Single-Parameter Sensitivity Analysis Method

Sensitivity analysis is performed to investigate the variation trend and sensitivity degree of the optimization objective to the change of each ply parameter. The purpose of sensitivity analysis is to identify which ply parameters are significant and which are insignificant to the blade performance [19]. Ply stacking sequence is a discrete variable and is an insensitive parameter that affects blade performance. In this study, ply angle and biaxial fabric ply thickness ratio are considered as independent variables; meanwhile, Tsai-Wu failure factor and maximum displacement are tested separately, as the evaluation index of the static strength and stiffness of the blade. In addition, the single-parameter sensitivity analysis on the blade performance is studied. The procedure can be described as:

(1) The mathematical model relating the optimization objective to the ply parameters is established

When the sensitivity of the blade performance P, affected by parameter α_k, is analyzed, the other parameters are considered as the reference value, and α_k takes values within an allowable range. The mathematical relation P-α_k is constructed as follows:

$$P = f\left\{\alpha_1^*, \ldots, \alpha_{k-1}^*, \alpha_k, \alpha_{k+1}^*, \ldots, \alpha_n^*\right\} \quad (1)$$

Reference value is the actual recommended value of each parameter. The mathematical relation between layer parameters and blade performance can be established using the unary quadratic regression analysis method. The sensitivity of P in relation to α_k can be obtained by observing the evolution of their curve.

(2) Dimensionless treatment

In sensitivity analysis, the units of each parameter are usually different, so it is impossible to compare and evaluate the sensitivity of each parameter. Therefore, dimensionless processing is required. The ratio of relative error $\delta_P = |\Delta P|/P$ of the system performance P to relative error $\delta_{\alpha k} = |\Delta\alpha_k|/\alpha_k$ of the parameter α_k is defined as the sensitive function $S_k(\alpha_k)$ of α_k. It can be described as:

$$S_k(\alpha_k) \triangleq \left(\frac{\Delta P}{P}\right) \Big/ \frac{|\Delta\alpha_k|}{\alpha_k} = \left|\frac{\Delta P}{\Delta\alpha_k}\right| \frac{\alpha_k}{P} \quad k = 1, 2, \ldots, n \tag{2}$$

When $|\Delta\alpha_k|/\alpha_k$ is small, $S_k(\alpha_k)$ can be approximately transformed into:

$$S_k(\alpha_k) = \left|\frac{dP(\alpha_k)}{d\alpha_k}\right| \frac{\alpha_k}{P} \quad k = 1, 2, \ldots, n \tag{3}$$

(3) Sensitivity comparison and analysis

The sensitivity function curve S_k-α_k can be given by Eq. (3), and the disturbance sensitivity of P to α_k can be further obtained by analyzing its variation trend. The sensitivity factor S_k^* of α_k can be obtained by substituting the reference value α_k^* into the sensitivity function, as illustrated in Eq. (4).

$$S_k^* = S_k(\alpha_k^*) = \left|\left(\frac{dP(\alpha_k)}{d\alpha_k}\right)_{\alpha_k=\alpha_k^*}\right| \frac{\alpha_k^*}{P^*} \quad k = 1, 2, \ldots, n \tag{4}$$

The influence of each parameter on blade performance can be obtained by comparing the S_k^* of different parameters. The larger the sensitivity factor is, the more obvious the effect on the system performance, as caused by minor parameter variation, is.

4 Sensitivity Analysis of Ply Angle in Relation to Blade Performance

4.1 Test Design and Analysis Results

According to the designed test scheme for the composite blade skin, the ply thickness ratio of biaxial fabric is at 40% of the recommended value, the ply stacking sequence is $[(0°, \pm A°)_{t1}/(\pm A°)_{t2}]_{NT}$, and the ply angle ranges from 30° to 60° at an increment step of 5°. The Tsai-Wu failure factor and the maximum displacement at different ply angles are calculated using the ABAQUS software (Tab. 2). Indicatively, the results of the first test group are listed in Fig. 4, as a full account would be too lengthy.

Table 2: Designed test scheme and analysis results at different ply angles

Ply Angle	Tsai-Wu Failure Factor	Maximum Displacement (mm)
$[(0°, \pm 30°)_{t1}/(\pm 30°)_{t2}]_{NT}$	0.8921	1089.70
$[(0°, \pm 35°)_{t1}/(\pm 35°)_{t2}]_{NT}$	0.8757	1089.28
$[(0°, \pm 40°)_{t1}/(\pm 40°)_{t2}]_{NT}$	0.8622	1089.49
$[(0°, \pm 45°)_{t1}/(\pm 45°)_{t2}]_{NT}$	0.8515	1090.36
$[(0°, \pm 50°)_{t1}/(\pm 50°)_{t2}]_{NT}$	0.8452	1091.86
$[(0°, \pm 55°)_{t1}/(\pm 55°)_{t2}]_{NT}$	0.8444	1093.96
$[(0°, \pm 60°)_{t1}/(\pm 60°)_{t2}]_{NT}$	0.8491	1096.53

4.2 Mathematical Modeling of the Effect of Ply Angle on Tsai-Wu Failure Factor and Maximum Displacement

Following Weierstress' Theorem for Best Polynomial Approximation, almost any type of function can be approximated by a polynomial [11]. In this study, the quadratic polynomial regression model in one variable was chosen to describe the changing rule of strength and stiffness. The simulation data of

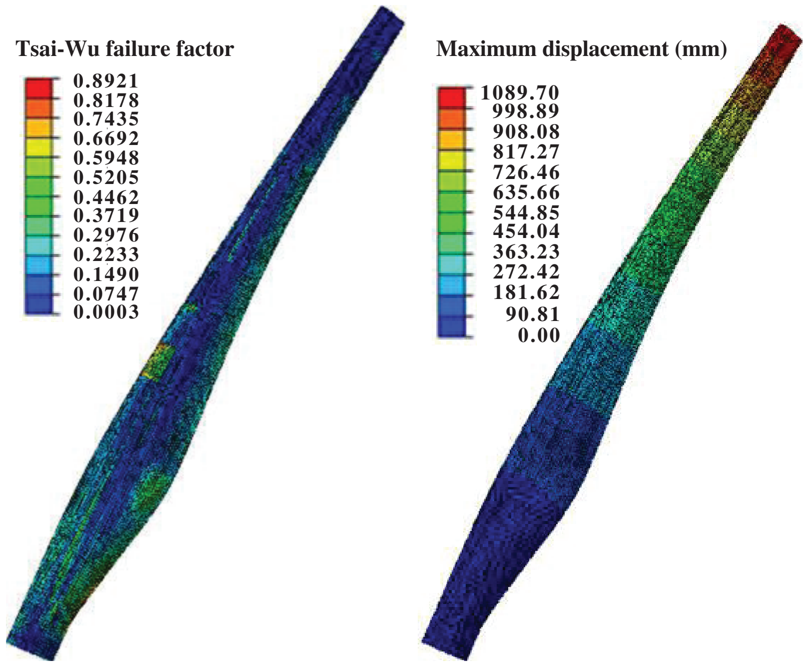

Figure 4: Tsai-Wu failure factor and maximum displacement of the first test group

Tsai-Wu failure factor and maximum displacement are analyzed using the Design-Expert software. Following, the polynomial regression model describing the effect of ply parameters on Tsai-Wu failure factor and maximum displacement respectively, can be obtained as:

$$Y_{\mathrm{T}}^{\mathrm{A}} = 1.08865 - 9.04 \times 10^{-3} A + 8.39048 \times 10^{-5} A^2 \tag{5}$$

$$Y_{\mathrm{U}}^{\mathrm{A}} = 1104.76238 - 0.86957A + 0.01222A^2 \tag{6}$$

where, $Y_{\mathrm{T}}^{\mathrm{A}}$ denotes the Tsai-Wu failure factor, $Y_{\mathrm{U}}^{\mathrm{A}}$ denotes the maximum displacement (mm), and A represents the ply angle.

In order to verify the reliability of the simulation data and the significance of the quadratic regression model, statistical tests of ANOVA (analysis of variance) must be realized. According to ANOVA, the p-value of the model is less than 0.0001, meaning that the quadratic regression model is highly accurate, from the engineering point of view.

The variance calculation result of the Tsai-Wu failure factor regression model is summarized in Tab. 3. The p-value of the Tsai-Wu failure factor regression model is 0.0000063, which is less than 0.0001, indicating that the model is significantly accurate. Similarly, the p-value of the maximum displacement regression model is 0, meaning that this model is also very precise.

The changing curves of Tsai-Wu failure factor and maximum displacement in relation to ply angle are illustrated in Fig. 5.

Comparative analysis shows that, as the ply angle grows from 30° to 60°, Tsai-Wu failure factor firstly decreases and then increases, while 53.87° appears to be the demarcation point. At 35.58° being the demarcation point, the maximum displacement first decreases and then increases. The two curves intersect near 45°, that is to say, Tsai-Wu failure factor and the maximum displacement reach their respective comprehensive optimal values near 45°, at which point the blade performance is evidently enhanced.

Table 3: Variance analysis result of Tsai-Wu failure factor regression equation

	Degree of Freedom	Sum of Squares	Mean Square	*F*	*P(Prob > F)*
Model	2	1.9200×10^{-3}	9.61835×10^{-4}	795.218	6.29369×10^{-6}
Error	4	4.8381×10^{-6}	1.20952×10^{-6}	—	—
Cor. Total	6	0.00193	—	—	—

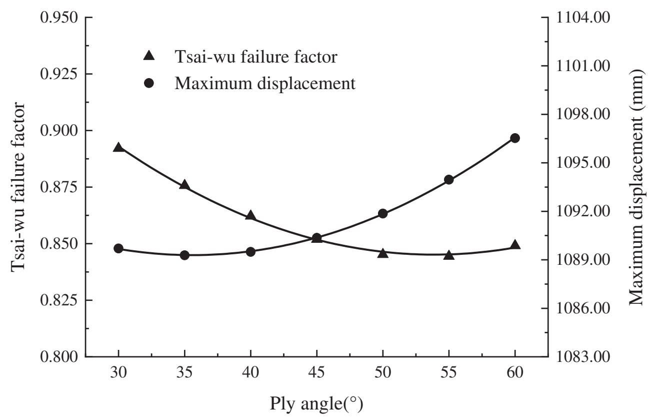

Figure 5: Changing curve of Tsai-Wu failure factor and maximum displacement in relation to ply angle

4.3 Sensitivity Function of Ply Angle in Relation to Blade Performance

According to the principle of single-parameter sensitivity analysis, the dimensionless processing of Eqs. (5) and (6) using Eq. (3) is carried out, and the sensitivity functions of ply angle to blade static strength and stiffness are obtained respectively, as shown in Eqs. (7) and (8).

$$S_{\mathrm{T}}(A) = \left|\frac{dY_{\mathrm{T}}^{\mathrm{A}}(A)}{dA}\right| \frac{A}{Y_{\mathrm{T}}^{\mathrm{A}}(A)} = \frac{\left|1.6781 \times 10^{-4}A^2 - 0.00904A\right|}{8.39048 \times 10^{-5}A^2 - 0.00904A + 1.08865} \tag{7}$$

$$S_{\mathrm{U}}(A) = \left|\frac{dY_{\mathrm{U}}^{\mathrm{A}}(A)}{dA}\right| \frac{A}{Y_{\mathrm{U}}^{\mathrm{A}}(A)} = \frac{\left|0.02444A^2 - 0.86957A\right|}{0.01222A^2 - 0.86957A + 1104.76238} \tag{8}$$

where, $S_{\mathrm{T}}(A)$ is the sensitivity of ply angle in relation to blade static strength and $S_{\mathrm{U}}(A)$ is the sensitivity of ply angle in relation to blade static stiffness.

5 Sensitivity Analysis of Biaxial Fabric Ply Thickness Ratio in Relation to Blade Performance

5.1 Test Design and Analysis Results

According to the engineering practice, a test scheme is designed for the composite blade skin, where the ply angle is at 45°, being the recommended value, the stacking sequence is $[(0°, \pm45°)_{t1}/(\pm45°)_{t2}]_{NT}$ and the biaxial fabric ply thickness ratio changes from 20% to 60% at an increment step of 10%. The Tsai-Wu failure factor and the maximum displacement at different ply thickness ratios of biaxial fabric are calculated using the ABAQUS software (Tab. 4).

5.2 Mathematical Modeling of the Effect of Biaxial Fabric Ply Thickness Ratio on Tsai-Wu Failure Factor and Maximum Displacement

The simulation data of Tsai-Wu failure factor and maximum displacement are analyzed using the Design-Expert software. Following, the polynomial regression model, describing the effect of biaxial

Table 4: Designed test scheme and analysis results at different ply thickness ratios of biaxial fabric

Biaxial Fabric Ply Thickness Ratio	Tsai-Wu Failure Factor	Maximum Displacement (mm)
20%	0.8513	1089.84
30%	0.8510	1090.03
40%	0.8515	1090.36
50%	0.8528	1090.83
60%	0.8549	1091.45

fabric ply thickness ratio on Tsai-Wu failure factor and maximum displacement, respectively, can be obtained as:

$$Y_{\mathrm{T}}^{\mathrm{B}} = 0.8543 - 0.023B + 0.04B^2 \tag{9}$$

$$Y_{\mathrm{U}}^{\mathrm{B}} = 1089.894 - 1.69429B + 7.14286B^2 \tag{10}$$

where, $Y_{\mathrm{T}}^{\mathrm{B}}$ denotes the Tsai-Wu failure factor, $Y_{\mathrm{U}}^{\mathrm{B}}$ denotes the maximum displacement (mm) and B represents the biaxial fabric ply thickness ratio.

The p-value of the Tsai-Wu failure factor and maximum displacement regression model are 0.0000001 and 0.0000068, respectively, that is, less than 0.0001. This means that the models are quite accurate.

The changing curves of Tsai-Wu failure factor and maximum displacement to biaxial fabric ply thickness ratio are shown in Fig. 6.

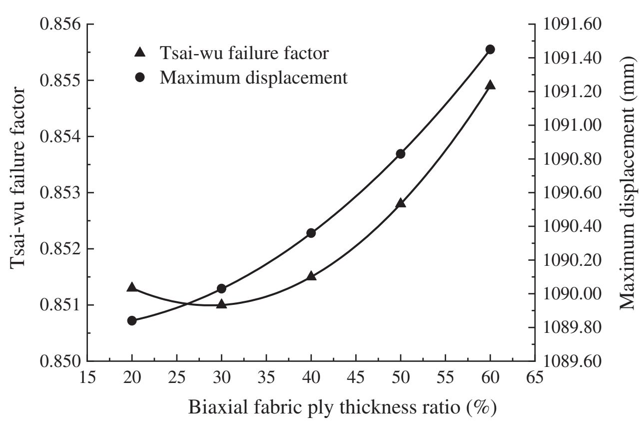

Figure 6: Changing curve of Tsai-Wu failure factor and maximum displacement in relation to biaxial fabric ply thickness ratio

Based on comparative analysis, it can be deducted that, as the biaxial fabric ply thickness ratio increases from 20% to 60%, with 28.75% as the demarcation point, Tsai-Wu failure factor first decreases and then increases. This means that the Tsai-Wu failure factor is at its lowest value and the static strength of the blade is optimal, when biaxial fabric ply thickness ratio increases to 28.75%. The graph shows that the maximum displacement increases continuously. When the biaxial fabric ply thickness ratio is at 20%, the maximum displacement is at its minimum, and the static stiffness of blade is optimal.

5.3 *Sensitivity Function of Biaxial Fabric Ply Thickness Ratio to Blade Performance*

The dimensionless processing of Eqs. (9) and (10) by Eq. (3) is carried out, and the sensitivity functions of biaxial fabric ply thickness ratio to blade static strength and stiffness are obtained respectively, as shown in Eqs. (11) and (12).

$$S_{\mathrm{T}}(B) = \left|\frac{dY_T(B)}{dB}\right| \frac{B}{Y_T(B)} = \frac{\left|0.08B^2 - 0.023B\right|}{0.04B^2 - 0.023B + 0.8543} \tag{11}$$

$$S_{\mathrm{U}}(B) = \left|\frac{dY_U(B)}{dB}\right| \frac{B}{Y_U(B)} = \frac{\left|14.28572B^2 - 1.69429B\right|}{7.14286B^2 - 1.69429B + 1089.894} \tag{12}$$

where, $S_{\mathrm{T}}(B)$ is the sensitivity of biaxial fabric ply thickness ratio to blade static strength, $S_{\mathrm{U}}(B)$ is sensitivity of biaxial fabric ply thickness ratio to blade static stiffness.

6 Comprehensive Contrast Analysis on Sensitivity of Ply Angle and Biaxial Fabric Ply Thickness Ratio

6.1 *Comprehensive Contrast Analysis on the Sensitivity of Blade Strength*

The sensitivity curves of ply angle and biaxial fabric ply thickness ratio in relation to blade static strength, as obtained from Eqs. (7) and (11), are shown in Fig. 7.

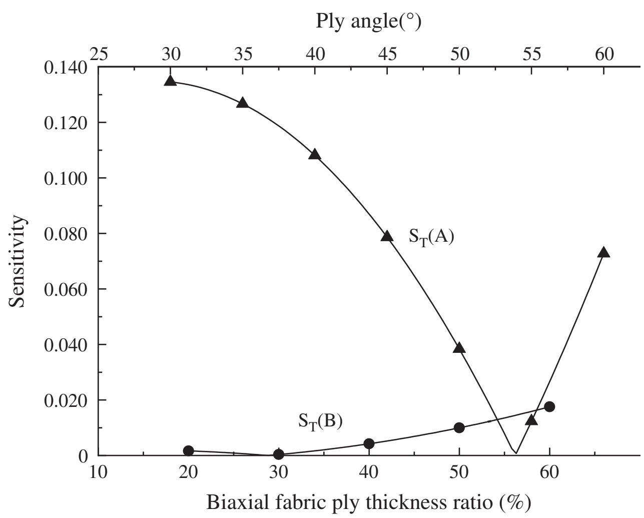

Figure 7: Comprehensive comparative analysis of sensitivity to blade static strength

It can be seen that the intersection point of sensitivity curve $S_{\mathrm{T}}(A)$ and ply angle is at (53.87°, 0). Under the condition that other ply parameters remain constant, as the ply angle increases from 30° to 60°, the demarcation point appears to be at 53.87°, as the sensitivity of ply angle to blade static strength first decreases and then increases rapidly. According to the graph, the intersection point of sensitivity curve $S_{\mathrm{T}}(B)$ and biaxial fabric ply thickness ratio is at (28.75%, 0). Under the condition that other ply parameters remain the same, as the biaxial fabric ply thickness ratio increases from 20% to 60%, the demarcation point stands at 28.75%. The sensitivity of biaxial fabric ply thickness ratio to blade static strength initially decreases slowly, followed by a gradual increase.

Specifically, the base value of ply angle and biaxial fabric ply thickness ratio is 45° and 40%, respectively, and the sensitivity factor of ply angle, biaxial fabric ply thickness ratio to blade static strength calculated by Eqs. (7) and (11) are 0.07864 and 0.00423, respectively. This indicates that the ratio of the sensitivity of ply angle to blade static strength is greater than the biaxial fabric ply thickness ratio.

6.2 Comprehensive Contrast Analysis on the Sensitivity of Blade Static Stiffness

The sensitivity curves of ply angle and biaxial fabric ply thickness ratio to blade static stiffness, as obtained from Eqs. (8) and (12), are illustrated in Fig. 8.

It is evident that the intersection point of sensitivity curve $S_U(A)$ and ply angle is at (35.58°, 0). Under the condition that other ply parameters remain constant, as the ply angle increases from 30° to 60°, the demarcation point is at 35.58°. The sensitivity of ply angle to blade static stiffness first decreases and then increases rapidly. Another observation is that, under the condition of other ply parameters remaining the same, the sensitivity of biaxial fabric ply thickness ratio to the blade static stiffness gradually increases.

Similarly, the sensitivity factors of ply angle and biaxial fabric ply thickness ratio to blade static stiffness, as calculated by Eqs. (8) and (12), are 0.00950 and 0.00148, respectively. The ratio of sensitivity of ply angle to blade static stiffness is greater than the biaxial fabric ply thickness ratio.

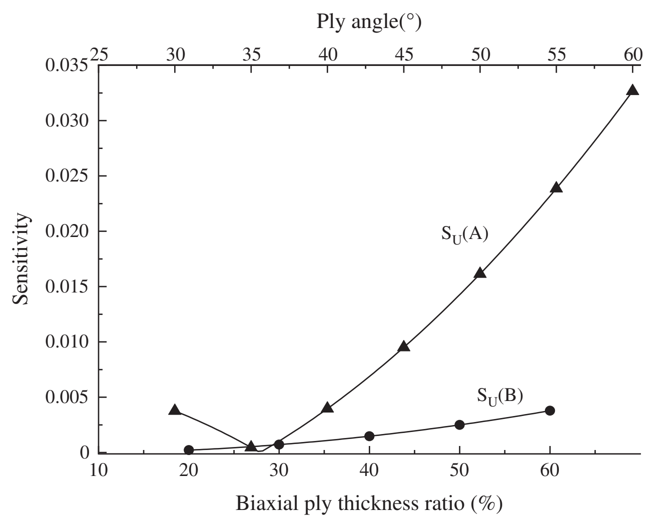

Figure 8: Comprehensive comparative analysis of sensitivity to blade static stiffness

7 Conclusion

This study presented a method on single-parameter sensitivity analysis, applied to investigate the sensitivity of key ply parameters in the composite layering process. The authors provided a changing rule of ply parameter to blade performance and optimal values for ply angle and biaxial fabric ply thickness ratio. The results can be summarized as follows:

As the ply angle increases, Tsai-Wu failure factor and maximum displacement of blade first decrease and then increase. Approximately at 45°, the blade performance appears significantly optimized.

As the biaxial fabric ply thickness ratio increases, Tsai-Wu failure factor of blade first decreases and then increases, showing optimal behavior at 28.75%. The maximum displacement continuously increases, while the optimal point appears at 20%.

The sensitivity of ply angle to Tsai-Wu failure factor and the maximum displacement of blade both first decrease and then increase rapidly. The sensitivity of biaxial fabric ply thickness ratio to Tsai-Wu failure factor of blade first decreases and then increases, as the maximum displacement increases gradually.

The static strength and static stiffness of wind turbine blade are more sensitive to the variation of ply angle than that of the biaxial fabric ply thickness ratio. This means that, compared to the biaxial fabric ply thickness ratio, the slightest variation of ply angle can cause significant change in the blade static strength and static stiffness.

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