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Coupling effects analysis of laminating parameters to static strength and stiffness of wind turbine blade

Zongtao Wang[2], Pengwen Sun[23,4], Lei Niu[2], Lanting Zhang[2]

Abstract. The effect of laminating parameterson performanceof blade is coupled. Based on the orthogonal experiment method, main layer angle, 0° lamination ratio and layer sequence as experiment factors,Tsai-Wu failure factor and maximum placement as static strength and stiffness index,orthogonal experiment table is designed, and mathematical models of orthogonal experiment analysis is established. Strength and stiffness of different factors level combination is simulated, and the influence on blade's structural performanceis analyzed. Average value of influencing effect and rang for test factors are calculated. Result indicates that 0° lamination ratio has great influence, and 0° lamination ratio and stacking sequence have couplingeffects on structuralproperties of blade. Layer scheme is optimized, and the blade's performance is increased. The correctness and effectiveness of the method is verified.

Key words. Structural properties, orthogonal experimental design, coupling effects, laminating parameters, wind turbines.

1. Introduction

As the key componentto capture wind energy,the motion state and forcesituation of blade arevery complex. It'sbetterdesign and superior performance are one of the decisive factors to ensure the normal and stable operation of wind turbines[1]. The performance of composite structure depends not only on the material prop-

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[2]Workshop 1 - School of Mechanical Engineering, Inner Mongolia University of Technology, Hohhot, Inner Mongolia010051, China

[3]Workshop 2 - Key Laboratory for Wind and Solar Power Energy Utilization Technology, Ministry of Education and Inner Mongolia Construction, Hohhot, Inner Mongolia 010051, China

[4]Corresponding author: Pengwen Sun; e-mail: pwsun@imut.edu.cn

erties, but also on the laminatingdesign and molding method. Many studies and engineering practices showedthat blade properties differ from different combinations of laminating parameters, and there is coupling effect of laminating parameters on blade property. Therefore, determining reasonable laminating parameters that affect blade performance is the key to ensure its quality[2].

In the research ofthis area, Finite element method was adoptedto analyze the rootfatiguefailure of composite wind turbine blade[3]. Monteused multi-objective genetic algorithm to optimize structural parameters, reduced weight and improved stiffness of blade[4]. Through analyzing and comparing the representative lay-up scheme of differentparameters, The effect of single laminating parameter on static structure performance of blade was studied[5]. It can be seen from the above that influence and optimization of laminating parameters on blade's structural performance were attracting more attention. Although some research results have been obtained, but the research is limited. Only influence of a single parameter was explored, or it is limited to coupling effect between two lay-up angles, no other laminating parameters are involved.

Therefore, taking laminating angle, 0° laminating ratio and stacking sequence as the experimental factors, Tsai-Wu failure factor and maximum placement as static strength and stiffness index, the orthogonal experiment design table is established based on orthogonal experiment method. The blade's performance of different factor combination is simulated, and mathematical statistics analysis of results is done. The coupling effect of two laminating parameters on blade performance will be explored in this paper.

2. Orthogonal Experiment Design

Combined of mathematical statistics and orthogonality principle,orthogonal experiment design is a scientific method of arranging reasonably multi-factor experiment by certain rules, shortening experimental period and avoiding blindness. Its design principle is to use the smallest orthogonal table under the premise that all experiment factors and interactions are included.The experiment result can be analyzed by means of range method, variance method and regression analysis method, and valuable conclusion can be obtained.

The equal-level of orthogonal experiment table is expressed by $L_m(N^p)$.

where L is orthogonal table, m is row number (test number),N is level number of factor, p is columnnumber (the maximum number of factors allowed to arrange).

Taken 1.5MW wind turbine blade, which is a typical representative, as an research object. This blade adopts Aerodyn and NACAmodified airfoil. Its length is 40.3m, and the diameter of wind wheel is 82.5m. Since the maximum stresses is present to the root part and middle part of blade, and laminating optimization are mainly concentrated in this region, two-third part(0-28.75m) off the blade rootis taken as the study object.

The experimental factors determined and the four levels for each factor respectively are layer angles A(35°, 40°, 45° and 50°), 0° lamination ratio B(40%, 30%, 20% and 10%) and stacking sequence C ($[\pm x\ /(0°,\ \pm x°)_4/\pm x°]_{NT}$, $[\pm x\ /(0°,$

$\pm x^\circ)_2/\pm x^\circ/(0^\circ, \pm x^\circ)_2]_{NT}$, $[(0^\circ, \pm x^\circ)_4/(\pm x^\circ)_2]_{NT}$, $[(0^\circ, \pm x^\circ)_2/(\pm x^\circ)_2/(0^\circ, \pm x^\circ)_2]_{NT}$).

Considering the feasibility and complexity of the test method, only the influence of layer angle and stacking sequence, 0° laminating ratio and stacking sequence on blade performance of are discussed. The experiment is two-factor four-level experiment, and first-level interaction of two factors is studied.

Degree of freedom of factor:

$$f_C = N - 1 = 4 - 1 = 3 \tag{1}$$

Degree of freedom of interaction:

$$f_i = f_{c1} \times f_{c2} = 3 \times 3 = 9 \tag{2}$$

The total degree freedom of Experiment:

$$f_T = f_{c1} + f_{c2} + f_i = m - 1 \tag{3}$$

The total number of tests 16, so the orthogonal experimental table $L_{16}(4^5)$ meets the requirement. Among which experimental factors account for 2 columns, interaction occupies3 columns.

Range method analysis compares synthetically the influential effect of experiment results and obtains the optimal experiment level and combination. Range is used to represent the difference between the maximum and minimum value of variation-amount in statistical data and evaluate the each level dispersion of factor.It reflects the variable range of experiment result caused by the level change. The biggerthe range is, the larger the influence of factor's different level on test result is. Contrarily, the influence is the smaller.

$$R = K_{\max} - K_{\min} \tag{4}$$

3. Effect analysis of laminatingparameter on blade performance based on orthogonal design method

3.1. Effect analysis of laminatingangle and stacking sequence on blade performance

In the orthogonal experiment table, the different factor levels of laminating angle A and stacking sequence C were arranged respectively in the first and second column. The first-level interaction between A and C was arranged in the third, fourth and fifth column, which can be considered as the other three factors that affect experiment result. The numbers 1, 2, 3, 4 in columns represent respectively the four levels of interaction. Simulation were analyzed according to the experiment arrangement of orthogonal table, and the Tsai-Wu failure factor and maximum displacement of 16group experimentsfor blade were obtained.As shown in table 1.

Table 1. Arrangement and simulation results of 16 group experiments

Test No.	Laminating angle	Stacking sequence	Interaction of A and C			Tsai-Wu failure factor	Maximum displacement(mm)
1	A_1	C_1	1	1	1	0.8501	998.5
2	A_1	C_2	2	2	2	0.8601	999.4
3	A_1	C_3	3	3	3	0.8607	999.3
4	A_1	C_4	4	4	4	0.9174	998.2
5	A_2	C_1	2	3	4	0.8326	998.7
6	A_2	C_2	1	4	3	0.8481	999.6
7	A_2	C_3	4	1	2	0.8533	999.4
8	A_2	C_4	3	2	1	0.9062	998.5
9	A_3	C_1	3	4	2	0.8263	999.4
10	A_3	C_2	4	3	1	0.8369	1000.0
11	A_3	C_3	1	2	4	0.8447	1000.0
12	A_3	C_4	2	1	3	0.8986	998.9
13	A_4	C_1	4	2	3	0.8161	1000.0
14	A_4	C_2	3	1	4	0.8273	1001.0
15	A_4	C_3	2	4	1	0.8351	1001.0
16	A_4	C_4	1	3	2	0.8916	999.9

The change curve of factor level and experiment index drawn by simulation result is shown as Figure 1 and Figure 2 respectively.

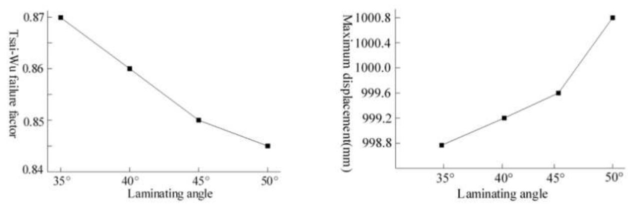

Fig. 1. Change curve of test index under different laminating angle

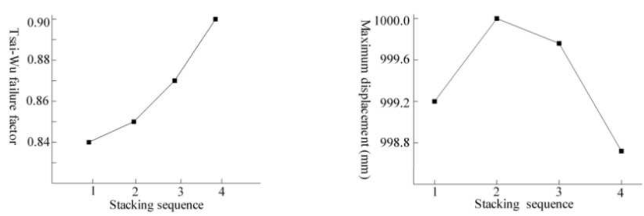

Fig. 2. Change curve of test index under different layer sequence

It can be seen that the optimal level of laminating angle and stacking sequence are respectively the fourth level A_4 and the first level C_1 when Tsai-Wu failure factor is taken as the main index of blade strength, and the optimal combination of experiment is the thirteenth group experiment $A_4C_1$when there is no or less coupling influence of two factors. The optimal level of laminating angle and stacking sequence are respectivelythe first level A_1 and the fourth level $C_4$when maximum displacement is taken as the main index of blade stiffness, and the optimal combination of experiment is the fourth group experiment $A_1C_4$when there is no or less coupling influence of two factors. Known from Table 1, the Tsai-Wu failure factor of the thirteenth group and the maximum displacement of the fourth group arethe minimum, and the optimum level combination corresponds to the optimal index.This indicates that the coupling effect of the two factors on blade strength and stiffness is not obvious.

The optimum result of laminating angle obtained by different main indexes is different. With laminating angle from 35° to 50°, the Tsai-Wu failure factor decreases and the maximum displacement increases.That is to say the blade strength increases and stiffness decreases.Comprehensively taking into account blade strength and stiffness, and practical application angle of double-axis cloth and triple-axis cloth, the optimum laminating angle is determined as 45°, that is, the third level A_3.

The k and R values calculated are shown as in table 2.

Table 2. $k$and Rvalue of Tsai-Wu failure factor

	Tsai-Wu failure					Displacement				
	Laminating angle	Stacking sequence	Interaction of A and C			Laminating angle	Stacking sequence	Interaction of A and C		
k_1	0.872	0.831	0.859	998.9	999.2	999.5	999.5	999.5	999.5	999.5
k_2	0.860	0.843	0.857	999.1	1000.0	999.5	999.5	999.5	999.5	999.5
k_3	0.852	0.873	0.855	999.6	999.9	999.5	999.5	999.4	999.5	999.4
k_4	0.843	0.903	0.856	1000.5	998.9	999.4	999.6	999.5	999.6	999.5
R	0.029	0.072	0.004			1.6	1.1	0.2		

The influence of each factor on test result is compared by range value. Taking Tsai-Wu failure factor as experimental index, the influence of stacking sequence on the blade strengthisgreater than that of laminating angle.Taking maximum displacement as experimental index, the influence of laminating angle on blade stiffnessis greater than that of stacking sequence.The coupling effect of laminating angle and stacking sequence is not obvious.

3.2. Effect analysis of 0° laminating ratio and stacking sequence on blade performance

In the orthogonal experiment table, the different factor levels of 0° laminatingratioB and stacking sequence C were arranged respectively in the first and second column. The first-level interaction between B and C was arranged in the third, fourth and fifth column. Simulation were analyzed according to the experiment arrangement of orthogonal table, and the Tsai-Wu failure factor and maximum displacement of 16group experimentsfor blade were obtained.As shown in table 3.

Table 3. Arrangement and simulation results of 16 group tests

Test No.	0° lamination ratio	layer sequence	Interaction of B and C			Tsai-Wu failure factor	Maximum displacement(mm)
1	B_1	C_1	1	1	1	0.8300	989.4
2	B_1	C_2	2	2	2	0.8621	990.2
3	B_1	C_3	3	3	3	0.8347	991.1
4	B_1	C_4	4	4	4	0.8599	990.0
5	B_2	C_1	2	3	4	0.8263	999.4
6	B_2	C_2	1	4	3	0.8369	1000.0
7	B_2	C_3	4	1	2	0.8447	1000.0
8	B_2	C_4	3	2	1	0.8986	998.9
9	B_3	C_1	3	4	2	0.8532	1011.0
10	B_3	C_2	4	3	1	0.8626	1012.0
11	B_3	C_3	1	2	4	0.8722	1011.0
12	B_3	C_4	2	1	3	0.9295	1010.0
13	B_4	C_1	4	2	3	0.9036	1024.0
14	B_4	C_2	3	1	4	0.9123	1025.0
15	B_4	C_3	2	4	1	0.9245	1025.0
16	B_4	C_4	1	3	2	0.9870	1023.0

The change curve of factor level and experiment index drawn by simulation result is shown as Figure 3 and Figure 4 respectively.

It can be seen that the optimal level of 0° lamination ratio and stacking sequence are respectively the first level B_1 and the first level C_1 when Tsai-Wu failure factor is taken as the main index of blade strength, and the optimal combination of experiment is the firstgroup experiment $B_1C_1$when there is no or less coupling influence of two factors. The optimal level of 0° lamination ratio and stacking sequence are respectivelythe first level B_1 and the fourth level $C_4$when maximum displacement is taken as the main index of blade stiffness, and the optimal combination of experiment is the fourth group experiment $B_1C_4$when there is no or less coupling influence of two factors. Known from Table 4, the Tsai-Wu failure factor of the fifth group and the maximum displacement of the first group arethe minimum, and the optimum level combination doesn't correspond to the optimal index.This indicates that the coupling effect of the two factors on blade strength and stiffness is obvious. The k

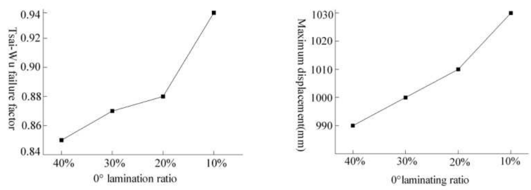

Fig. 3. Change curve of test indexunder different0 lamination ratio

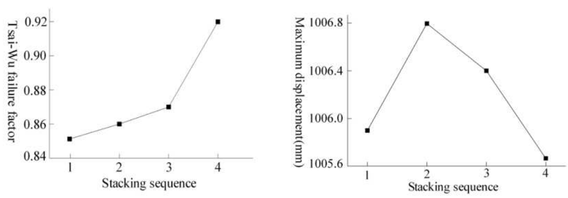

Fig. 4. Change curve of test indexunder different stacking sequence

and R values calculated are shown as in table 4.

Table 4$k$and $R$of Tsai-Wu failure factor and displacement

	Tsai-Wu failure					Displacement				
	0° laminating ratio	Stacking sequence	Interaction of B and C			0° laminating ratio	Stacking sequence	Interaction of B and C		
k_1	0.847	0.853	0.882	0.879	0.870	990.2	1006.0	1005.9	1006.1	1006.3
k_2	0.852	0.868	0.886	0.884	0.887	999.6	1006.8	1006.2	1006.0	1006.1
k_3	0.879	0.869	0.875	0.869	0.876	1011.0	1006.5	1006.2	1006.1	1006.6
k_4	0.932	0.919	0.868	0.869	0.868	1024.3	1005.8	1006.8	1006.8	1006.6
R	0.085	0.066	0.019			34.1	1.0	0.9		

The influence of each factor on test result is compared by range value.The influence of 0?laminating ratioon the blade strength and stiffness isgreater than that of stacking sequence.The coupling effect of laminating angle and stacking sequence is obvious.

4. Laminating Optimization of blade skins Structure

The strength and stiffness distribution of original laminating scheme of blade skins are shown as in Figure 5.

It was determined that the laminating angle is 45° in 3.1, which is the third level A_3. Known from 3.2, considering coupling effect of 0° laminating ratio and stacking sequence on blade performance,the optimal strength laminating scheme is $A_3B_2C_1$, and the optimal stiffness laminating scheme is $A_3B_1C_1$.The comparative analysis of the strength and stiffness of the original blade laminating scheme and the two optimal laminating schemes is shown as in Table 5.

Compared with the original laminating scheme, Tsai-Wu failure factor and maximum displacement of $A_3B_2C_1$ reduce about 0.0336 and 93.6mmrespectively, and those of $A_3B_1C_1$ reduce about 0.0299 and 103.6mm respectively. Allowed prebending at workingof blade is 1600mm, two kinds of optimal layer scheme can ensure that blade does not collide with the tower. In order to increase the static strength of blade, the final optimal laminating scheme is determined as$A_3B_2C_1$.

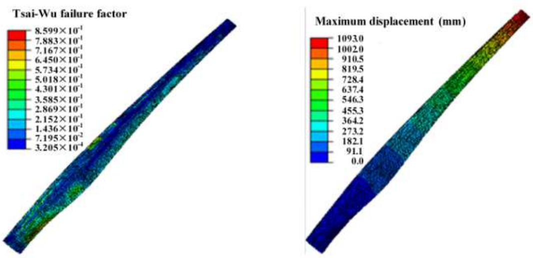

Fig. 5. Tsai-Wu failure factor and maximum displacement distribution of original laminating scheme of blade skins

Table 5. The analysis results of each layer scheme

layer scheme	Tsai-Wu failure factor	Maximum displacement (mm)
Originallayer scheme	0.8599	1093.0
$A_3B_2C_1$	0.8263	999.4
$A_3B_1C_1$	0.8300	989.4

5. Conclusion

The greatest influence on blade structural performance is 0° laminating ratio. In engineering practice, under the precondition that blade meets the requirements of anti-shear, the laminating ratio of 0° fiber cloth can be increased appropriately to improve structural performance of blade.The optimal result of laminating angle does not converge. With it from 35° to 50° the strength of blade increases and the stiffness decreases. The effect on strength and stiffness of blade is inconsistent. Comprehensive consideration, the optimum laminating angle is determined as 45° . The coupling effect of laminating angle and stacking sequence on blade structure performance is not obvious.There is a coupling relationship between stacking sequence and 0° laminating ratio, and their coupling effect on blade structure performance is greater.

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