Ply Parameters Optimization and Strength Reliability Analysis of Wind Turbine Blade

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Abstract. As the critical component of capturing wind energy, the performance and reliability of blade are directly related to the safe, stable operation and service life of wind turbines. The performance of the blade is mainly determined by the ply parameters, so it has important value to study the optimization method of ply parameters and the analysis method of strength reliability of wind turbine blade. In this paper, the load of a 1.5MW wind turbine blade under the DLC1.5g-2 working condition is calculated and its finite element model is established. Combined with engineering practice, the investigation range of ply parameters is determined, the test scheme is designed by using the mixed level uniform experiment method, and the blade strength is analyzed. Based on the polynomial regression analysis method and simulation results, the quadratic mathematical model between the ply parameters and the Tsai-Wu failure factors is established, and the range of ply parameters is optimized by mean value analysis method and interaction analysis method. On this basis, the ply parameters are regarded as random variables, and the structural performance function of blade failure is constructed. The reliability of the blade is predicted by the first-order second-moment method. The results show that the blade is reliable in the range of optimized ply parameters. The work provides the method and technical support for the laminate structure design and optimization of wind turbine blade.

1. Introduction
In the case of wind turbines, the critical component of capturing the wind energy, the blades, are subject to complicated loading conditions. The optimized design, the excellent performance and the reliable quality of blade are the determining factors to ensure normal operation of a wind turbine. The main performance indexes of wind turbine blade are strength, stiffness, reliability and stability, and the three key ply parameters are ply angle, ply thickness and ply stacking sequence. A lot of researches and engineering practices have shown that the ply parameters are the important factors to determine the performance of blade, different ply parameters lead to different performance of blade, and there is coupling effect on the blade performance by ply parameters[1-2]. It can be seen that the blade forming is a complex coupling process with multi-parameter and multi-objective. Therefore, it has important research value to optimize the range of ply parameters and predict the blade reliability within the optimized ranges of ply parameters.

A large amount of research work has been devoted to this field up to this day. In the paper of Hu et al. [3], an uncertainty model of dynamic wind load was established based on 249 sets of wind load data, and the cost of blade is reduced by optimizing the thickness of composite laminates.
Konstantinos et al. [4] pointed out that the laminate material of wind turbine blades has parameter variability. In order to ensure the safety and effectiveness of design, uncertainty related to basic variables were quantified and considered in the process of design calculation. Liu et al [5]. studied the reliability of offshore wind turbine blades. The structural model of blade was established by using ANSYS software, and the failure probabilities of root overload, root fatigue and tip excessive displacement were calculated in this article. The influence of floating foundation motion on the reliability of blades was analyzed. Huh et al. [6]. evaluated the fatigue life of GFRP (Glass-Fiber Reinforced Plastic) composites used in wind turbine blades considering the glass fiber orientations, and further studied the effect of stress ratio on fatigue life of composites blade. In the research of Cheng et al. [7], dynamic response of flexible multi-body tower blade coupling in large wind turbine was studied by joint simulation technology of multi parameter monitoring of large scale wind turbine tower blade coupling structure and the response analysis under different working conditions. In the paper of Hu et al. [8], the comprehensive fatigue analysis framework for composite wind turbine blades was developed, the finite element blade model was parameterized for detailed stress analysis, and reliability analysis of wind turbine blades for fatigue life under wind load uncertainty was studied. Ye et al. [9] proposed a multi-scale modeling strategy to investigate failure mechanisms and damage evolution of composite blades with initial defects from microscopic damage to macroscopic fracture, and it is demonstrated that the method was suitable to predict mechanical properties of complex composite structures effectively. He et al. [10] worked together to study the aerodynamic and engine room noise of large wind turbine blade by establishing a quadratic mathematical model. It can be seen that previous research works are lack of in-depth study on ply parameters optimization and reliability of wind turbine blade.

Therefore, taking a 1.5MW wind turbine blade as research object, the load of the blade under the DLC1.5g-2 working condition is calculated and its finite element model is established. The experimental scheme is design by the mixed level uniform experiment method, and the blade strength is analyzed. The nonlinear mathematical model between ply parameters and blade strength is established based on the polynomial regression analysis method. The coupling effect of pairwise ply parameters on blade strength is investigated, and the value range of ply parameters is optimized. On this basis, the ply parameters are regarded as random variables, the structural performance function of the blade is constructed, and the reliability of blade is predicted by using the first-order second-moment method.

2. Load Calculation and Finite Element Model of Blade
Mega-watt size wind turbine blades generally use the structure of main beam, double web, skin and soft sandwich material, as depicted in Fig. 1. Among them: the main beam mainly bears gravity, centrifugal force and bending moment load, and is supported by web. The inner and outer skin provides aerodynamic shape and bears part of bending load and most of shear load, and the soft sandwich material mainly plays a filling role.

The typical 1.5MW wind turbine blade adopts Aerodyn and NACA63 modified airfoil. The blade length is 40.25m, and the diameter of wind wheel is 82.5m. The maximum string length is 3.183m, and rated rotational speed is 17.4rpm, adapting to the wind farm level is IEC IIIA. The blade is divided into three segments along its spanwise direction, namely the root segment, the middle segment and the tip segment. Since most of the load on the blade during the wind turbine operation is concentrated in the root and the middle segment, the two segments, which are 0 to 28.2 m from the blade root, are selected as the research object.

The GH-Bladed software is applied 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 directions of a variety of the blade. The calculated loads of 15 sections of blade under DLC1.5g-2 limit working condition are summarized in Table 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) |
|------------------|-------------------------------|-----------------------------|
|                  | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ |
| 0.7m             | 0.2   | 0.0   | 7.9   | 141.3 | 33.7  | 0.0   |
| 1.4m             | 0.2   | 0.1   | 7.9   | 141.3 | 33.7  | 0.0   |
| 1.8m             | 1.1   | 2.2   | 2.3   | 80.9  | 19.3  | 0.0   |
| 3.2m             | 12.2  | 4.0   | 6.1   | 281.7 | 189.8 | 15.2  |
| 4.2m             | 0.6   | 2.6   | 4.2   | 197.5 | 60.9  | 0.6   |
| 6.5m             | 6.4   | 10.8  | 8.0   | 380.8 | 282.2 | 11.2  |
| 8.5m             | 4.8   | 12.7  | 7.1   | 359.7 | 105.3 | 0.5   |
| 11.2m            | 9.9   | 23.4  | 9.3   | 486.1 | 135.3 | 0.3   |
| 14.6m            | 10.4  | 26.2  | 8.7   | 465.3 | 117.5 | 0.2   |
| 16.7m            | 4.8   | 14.0  | 4.6   | 246.1 | 57.0  | 0.5   |
| 18.5m            | 3.3   | 10.9  | 3.1   | 188.3 | 41.6  | 0.8   |
| 22.2m            | 5.6   | 25.7  | 5.0   | 304.4 | 53.0  | 0.4   |
| 23.1m            | 1.1   | 0.3   | 1.0   | 64.4  | 13.7  | 0.6   |
| 25.7m            | 3.1   | 10.0  | 2.5   | 170.3 | 34.6  | 1.8   |
| 28.2m            | 2.1   | 11.4  | 2.3   | 137.0 | 14.6  | 0.3   |

The shell model of blade was built in UGNX software. According to the actual laying scheme, material properties were 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 of each section of blade, concentrated loads and bending moment loading in three directions are applied at the center of each section of blade respectively. Finite element model of 1.5 MW blade is shown as Fig. 3, and it consists of 132,781 elements and 65,772 nodes.

3. Test Design Scheme and Mathematical Model between Ply Parameters and Blade Strength

Uniform experimental design is a scientific and theoretical method to construct a uniform design table for experimental design based on the application principle of number theory in multidimensional numerical integration. The mixed level uniform test design is one of the uniform test designs. When the level number of experimental factors is different, the experimental scheme with the best uniformity and excellent information matrix can be obtained by the quasi-level method [11].

According to the engineering practice and experience, the range of the ply angle is 35° to 55° at an increment step of 5°, the range of the ±$x°$ ply thickness ratio is 20% to 60% at an increment step of 10%, and three representative and regular ply stacking sequence of $C_1$: [(0°,±$x°$)/±$x°$/(0°,±$x°$)/±$x°$], $C_2$: [(0°,±$x°$)/±$x°$/±$x°$/(0°,±$x°$)] and $C_3$: [(0°,±$x°$)/(0°,±$x°$)/±$x°$/±$x°$] are selected.

The test scheme is designed by the mixed level uniform test design. By using data processing system to perform quasi-level operations on different parameter levels, 15 groups of test schemes
are generated. The Tsai-Wu failure factors of the blade at each test scheme under the DLC1.5g-2 working condition are analyzed in ABAQUS software, and the results are shown in Table 2.

**Table 2.** Test design scheme and Tsai-Wu failure factor under DLC1.5g-2 working condition.

| No. | Ply Angle(°) | ±x° ply thickness ratio | Ply stacking sequence | Tsai-Wu failure factor |
|-----|--------------|-------------------------|-----------------------|------------------------|
| 1   | 45°          | 60%                     | C1                    | 0.8525                 |
| 2   | 50°          | 40%                     | C2                    | 0.8421                 |
| 3   | 55°          | 60%                     | C2                    | 0.8491                 |
| 4   | 45°          | 20%                     | C3                    | 0.8480                 |
| 5   | 40°          | 50%                     | C2                    | 0.8611                 |
| 6   | 35°          | 20%                     | C2                    | 0.8860                 |
| 7   | 55°          | 30%                     | C3                    | 0.9297                 |
| 8   | 40°          | 60%                     | C3                    | 0.8323                 |
| 9   | 55°          | 40%                     | C1                    | 0.8443                 |
| 10  | 40°          | 30%                     | C1                    | 0.8604                 |
| 11  | 50°          | 50%                     | C3                    | 0.8414                 |
| 12  | 35°          | 50%                     | C1                    | 0.8710                 |
| 13  | 35°          | 40%                     | C3                    | 0.8684                 |
| 14  | 45°          | 30%                     | C2                    | 0.8517                 |
| 15  | 50°          | 20%                     | C1                    | 0.8403                 |

Based on the polynomial regression analysis method, the quadratic mathematical model between parameters and response variables can be effectively established. It has high practical value and accuracy to analyze the coupling effect of the two factors [12-13].

The influence of parameters on the response has the influence of single parameter and coupling between different parameters, but there is no coupling effect between the same parameters. The nonlinear mathematical model between ply parameters and blade performance can be expressed as follows:

\[ F = \beta_0 + \beta_a a + \beta_b b + \beta_c c + \beta_{ab} ab + \beta_{bc} bc + \beta_{ac} ac \]  

(1)

Where, \( F \) denotes the response variable; \( a, b \) and \( c \) represent the ply angle, ±x° ply thickness ratio and the ply stacking sequence; \( ab, bc \) and \( ac \) represent coupling terms of \( a \) and \( b \), \( b \) and \( c \), \( a \) and \( c \); \( \beta_0 - \beta_6 \) represent coefficients.

The SPSS software is used to make polynomial regression analysis of the test data, and the quadratic mathematical model between the ply parameters and the Tsai-Wu failure factor of the blade can be obtained as:

\[ SF = 1.69475 - 0.02695 a + 0.00050 b - 0.21037 c + 0.00011 a b + 0.00316 a c + 0.00025 b c \]  

(2)

Where, \( SF \) denotes Tsai-Wu failure factor.

In order to verify whether the accuracy of the quadratic polynomial regression model meets the engineering requirements, the absolute deviations between the \( SF \) test value and the quadratic polynomial regression fitting value are calculated, as shown in Table 3. It can be seen that all deviations are less than 5%, and the fitting value meets the engineering requirements.

**Table 3.** Designed test scheme and calculated absolute deviation at different test scheme.

| No. | \( SF \)  | Fitting value of \( SF \) | Absolute deviation |
|-----|------------|---------------------------|--------------------|
| 1   | 0.8525     | 0.8731                    | 2.41%              |
| 2   | 0.8421     | 0.8461                    | 0.48%              |
| 3   | 0.8491     | 0.8587                    | 1.13%              |
| 4   | 0.8480     | 0.8430                    | 0.59%              |
4. Optimized Value Range of Ply Parameters
Not only the influence of single parameter, but also the coupling effect of ply parameters on blade performance should be considered in the optimization process of ply parameters.

4.1. The Optimized Value of Single Ply Parameter
Mean value analysis method is used to optimize the value range of single ply parameter. By fixing the single level of single factor, the twice mean value and mean difference of blade performance index are calculated, and the range of value is determined according to the value of mean difference.

The calculated mean values of Tsai-Wu failure factor corresponding to ply angle, ±x° ply thickness ratio and ply stacking sequence are shown in Table 4.

Table 4. The mean value analysis of Tsai-Wu failure factor.

| Ply angle | Mean value of SF | ±x° ply thickness ratio | Mean value of SF | Ply stacking sequence | Mean value of SF |
|-----------|-----------------|------------------------|-----------------|----------------------|-----------------|
| 35°       | 0.8654          | 20%                    | 0.8581          | C₁                   | 0.8495          |
| 40°       | 0.8512          | 30%                    | 0.8610          | C₂                   | 0.8580          |
| 45°       | 0.8507          | 40%                    | 0.8516          | C₃                   | 0.8514          |
| 50°       | 0.8413          | 50%                    | 0.8578          |                      |                 |
| 55°       | 0.8474          | 60%                    | 0.8799          |                      |                 |

The mean value of SF is recalculated again and obtained its mean difference. The minimum values of the mean difference of ply angle, ±x° ply thickness ratio and ply stacking sequence are 0.0072, 0.0048 and 0.0015, respectively. The corresponding ply angle is 40° and ±x° ply thickness ratio is 30%, and the ply stacking sequence is C₃. The Tsai-Wu failure factor of this set of ply parameters is the smallest and the blade strength is the highest.

4.2. Optimized Value Range of Coupling Ply Parameters
Because the influence of ply stacking sequence on blade strength is not significant, only considering the coupling effect of ply angle and ±x° ply thickness ratio on blade strength, the change relation curved surface between the ply angle, ±x° ply thickness ratio and blade strength can be obtained. Through judging the position of the lowest point and the trend of the two straight-line that constitute the lowest point, the optimized value range of ply parameters can be determined.

According to the analysis results in Table 3, the relation curved surfaces of Tsai-Wu failure factors, ply angle, and ±x° ply thickness ratio at different ply stacking sequence are listed in Fig. 3.
ply stacking sequence is C₁
(b) ply stacking sequence is C₂
(c) ply stacking sequence is C₃

Figure 3. Relation curved surface of Tsai-Wu failure factor, ply angle and ±x° ply thickness ratio at different ply stacking sequence.

Through compare and analysis, it can be deducted that the optimized ranges of the ply parameters are: ply angle within [40°, 50°], ±x° ply thickness ratio within [20%, 60%], ply stacking sequence is C₃. The blade strength is high when the ply parameters are in this range.

5. Reliability Analysis of Blade Strength
Strength is often one of the key considerations to judge whether the blade is invalid or not in engineering practice. When the stress endured by structure is less than strength, the structure will not fail, otherwise failure will occur. Defined stress and strength as \( S \) and \( R \), then the probability of reliable structure \( P_R \) is the probability of \( S > R \).

In the reliability analysis, a structural performance function is commonly used to represent the working state of a structure, it can be expressed as [14]:

\[
Z = g(x_1, x_2, \ldots, x_n)
\]  

(3)

Where, \( x_1, x_2, \ldots, x_n \) represent the basic random variables of the structure. When \( Z > 0 \), the structure is in a reliable state; otherwise, the structure is in a failure state.

The reliability of blade is the probability that the blade completes its predetermined function within the specified time and under the specified conditions. The reliability analysis of the blade is a process of quantitatively judging its safety degree or failure probability. In this process, the failure probability is generally obtained by studying its performance function [15].

For wind turbine blades, the resistance to failure is the strength, and the failure is caused by the Tsai-Wu failure factor. The design safety factor of blade should be greater than or equal to 1.15 [16]. The structural performance function of blade is constructed as follows:

\[
Z = g(x_1, x_2, \ldots, x_n) = 1 - 1.15SF
\]  

(4)

The reliable probability \( P_R \) of blade can be expressed as:

\[
P_R = P(Z > 0) = \int_{Z=0} \int \ldots \int f_z(x_1, x_2, x_n) dx_1 dx_2 \ldots dx_n
\]  

(5)

Since the probability density function \( f_z(x_1, x_2, x_3) \) is unknown, the failure probability of blade can be obtained by the solving reliability coefficient \( \beta \).

\[
P_F = \Phi(-\beta) = 1 - \Phi(\beta)
\]  

(6)

Where \( P_F \) denotes the failure probability of blade, \( \Phi \) denotes the standard normal distribution function.
The structural size of the finalized blade remains unchanged. Not considering the variation of wind load, only the ply parameters are regarded as random variables in this paper. It is difficult to give an exact analytical expression of the relation between ply parameters and blade strength. A nonlinear quadratic mathematical model of ply parameters and blade strength is used to simulate the structural performance function of blade failure [17]. Then the structural performance function of blade failure is:

\[ Z = g(a,b,c) = 1 - 1.15SF \]  

\[ = -0.94896 + 0.03099a - 0.00058b + 0.24193c - 0.0013ab - 0.00363ac - 0.00029bc \]  

(8)

When the structural performance function is expressed explicitly by random variables, the mathematical model with only mean and standard deviation is used in the case where the distribution of the basic random variables is unclear. The first-order second-moment method is adopted as the reliability analysis method. The structural performance function can be linearized by Taylor series expansion, and the original function is replaced by one-degree term [18].

Taylor series expansion of structural performance function is expressed as:

\[ Z = g(\mu_x) + \sum_{i=1}^{n} \frac{\partial g}{\partial x_i} (\mu_x - \mu_{x_i}) + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial^2 g}{\partial x_i \partial x_j} (\mu_x - \mu_{x_i})(\mu_x - \mu_{x_j}) + \cdots \]  

(9)

Removing quadratic term, the reliability coefficient \( \beta \) can be obtained as:

\[ \beta = \frac{\mu_x}{\sigma_x} \approx g(\mu_x, \mu_{x_i}, \cdots, \mu_{x_n}) \]  

\[ \sqrt{\sum \left( \frac{\partial g}{\partial x_i} \right)^2 \sigma_{x_i}^2} \]  

(10)

Where \( \mu_x \) denotes the mean of structural performance function, \( \sigma_x \) denotes the standard deviation of structural performance function, \( \mu_{x_i} \) denotes the mean of basic random variables, \( \mu \) represents the mean, \( \sigma_{x_i}^2 \) represents the variance of basic random variable.

When ply stacking sequence is C3, and the optimized ranges of ply angle and \( \pm x^\circ \) ply thickness ratio are within \([40^\circ, 50^\circ]\) and \([20\%, 40\%]\) respectively, the mean and variance of random variable of ply parameters are calculated. The results are shown in Table 5.

### Table 5. The calculated results of mean and variance of ply parameters.

| Variable | Unit | \( \mu_{x_i} \) | \( \sigma_{x_i}^2 \) |
|----------|------|----------------|----------------|
| a        | °    | 45             | 16.6667        |
| b        | %    | 30             | 66.6667        |
| c        |      | 3              | 0              |

By calculation, the reliability coefficient \( \beta = 2.4119 \), and the failure probability \( P_f = 1 - \Phi(2.4119) = 0.0079 \). It is indicated that the wind turbine blade is reliable in the optimized ranges of ply parameters.

### 6. Conclusion

The blade performance and reliability are directly related to the safe, stable operation and service life of wind turbines. The mixing level uniformity test method is used to design the test scheme. The quadratic mathematical model between ply parameters and Tsai-Wu failure factor is established based on the polynomial regression analysis method and analysis result of blade strength, and the accuracy of regression model is verified to meet the engineering requirements. The optimized ranges of ply parameters are obtained by using the single factor mean method and interaction analysis method. The value of Tsai-Wu failure factor is small and the strength is high when ply
angle and ±x° ply thickness ratio are within [40°, 50°] and [20%, 40%] respectively, ply stacking sequence is [(0°, ±x°)/(0°, ±x°)/(±x°)]r. The ply parameters are regarded as random variables, and the failure structural performance function of wind turbine blade associated with Tsai-Wu failure factor is constructed. The blade reliability within the optimized ranges of ply parameters is predicted by the first-order second-moment method. The reliability coefficient is 2.4119, and the failure probability $P_f$ is 0.0079. The blade is reliable and stable in the optimized ranges of ply parameters. The work provides the method and technical support for the laminate structure design and optimization of wind turbine blade.

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