Research on Structural Failure Analysis and Strengthening Design of Offshore Wind Turbine Blades

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Abstract: The existing blade protection mechanisms are highly dependent on the control system and its power supply. Safety of offshore wind turbines cannot be guaranteed under extreme weather when the control protection mechanisms fail. So far, not enough consideration has been given to the above problems in mechanical design for protecting wind turbine blades. In this paper, a reinforcing cable component (RCC) is proposed to improve the resistance ability of offshore wind turbine blades. The static model of the blades with reinforcing cable component was presented. The Finite Element (FE) simulation was performed for a 5 MW offshore wind turbine and load reduction effect of connection location for RCC was discussed according to the FE results. A static strain verification test was carried out. Simulation and test results indicate that the proposed reinforcing cable component effectively reduces the strain as well as the tip displacement of the blades. The proposed mechanical structure will help to enhance the survival ability of offshore wind turbine blades when the control protection system fails.

Keywords: wind turbine blades; steel cable connection; wind load; finite element method; structural stress; static load test

1. Introduction

Wind power has advantages of renewable, pollution-free, and cost-effective [1]. With the continuous development of wind power generation technology, megawatt wind turbines have been widely applied around the world. In 2021, the cumulative of global wind power reached 837 GW, the second highest in history [2]. For coastal areas with plenty wind energy, large offshore wind farms have been built and produced considerable economic benefits. Compared with onshore wind power, the offshore wind power has advantages of stable wind speed and less land costs [3]. As the Global Wind Report shows, the new installed capacity of offshore wind power reached a record high in 2021, with a new installed capacity of 21.1 GW. This figure is three times that of 2020, and the total installed capacity of offshore wind power is evaluated to reach 370 GW in 2030 [4].

Nevertheless, the offshore wind power has long faced questions about high maintenance difficulty and complex external loading [5,6]. As the demand for output power of wind turbine is increasing [7], the structure design of blades is upscaled towards a larger and more flexible direction [8,9]. For large offshore wind turbine blades, length in the spanwise direction are much larger than chord direction, thus the wind turbine blades are usually regarded as cantilever structures in structural analysis [10]. While the stiffness of the blades is decreased, the stability of the wind turbine is also decreased [11]. Chen and Xu [12] investigated the wind turbine failure using the post mortem analysis and demonstrated that the blade fracture was one of the major reason for structural failure of wind turbines. Chou et al. [13] pointed that the blade strength was crucial for safety of wind turbine under critical wind load through Finite Element (FE) analysis. Chen and Kam [14] investigated failure location of a composite sandwich wind blade subjected to wind load, and the rupture was observed at the blade root at extreme wind speed. Lee et al. [15] proposed that under
real load distribution the bumping motions of blades were the main reason for unfavorable load distribution at blade root.

At present, improving the survivability of wind turbines is mainly realized by yaw system and pitch system [16]. The simulation results of Bossanyi [17] clearly showed that the pitch system had a significant load reduction effect for large wind turbines. Stubkier et al. [18] researched the load reduction effect of a hydraulic soft yaw concept and the ultimate load reduction of up to 19% was achieved. However, it is possible that the yaw system and the pitch system encounter faults in extreme weather due to the fast-changing direction and large wind load of typhoon. Kim and Manuel [19] researched the influence of yaw error or pitch misalignment on the aerodynamic loading based on numerical studies. Bakhshi and Sandborn [20] indicated that the most susceptible site for failure is the blade root under yaw error. Similar problem was also observed in wind farm of China [21]. The super typhoon Rammasun in 2014 caused 3 wind turbines of Wenchang wind farm in Hainan province to suffer from structural failure, and blades of another 2 wind turbines were separated from root. The main reason for such powerful destruction is due to the failure of pitch system under sudden change of typhoon wind direction [22]. As the blades cannot alter the angle in time, the increased stress on the blade and the whole wind turbine gave rise to structural damage.

In this paper, a reinforcing cable component (RCC) is proposed to reduce the probability of offshore wind turbine damage. The proposed mechanical structure is independent of the present yaw or pitch system, thus the blades can still be protected when the control system is damaged. For a wind turbine that brakes at an unfavorable position, the RCC can apply control force to blades, thereby reducing the excessive wind load on blades and preventing the braking system from overload.

This paper is organized as follows. In Section 2, the unfavorable position for blades is obtained and the structural failure of blades is analyzed. In Section 3, the reinforcing cable component is proposed, and its wind load reduction mechanism is analyzed by establishing static mechanical model of blades with reinforcing cables. In Section 4, the wind load reduction effect of the proposed reinforcing cable component is researched by finite element method, and the connecting location for RCC is analyzed. Section 5 presents the comparative static strain test results for blades without and with RCC, followed by conclusions drawn in Section 6.

2. Structural Failure Analysis of Wind Turbine Blades

The external load of offshore wind turbine blade is complicated. According to the load source, the external load can be divided into aerodynamic loads, centrifugal loads and gravity loads [23]. Under extreme weather, the failure of the offshore wind turbine is closely related to the interaction between the wind turbine and the extreme winds [10]. Next, the wind load on blades is considered for structural failure analysis.

When the wind speed exceeds the cut-out wind speed under typhoon weather, the brake system will be started to protect the wind turbine from tower collapse and impeller failure. During extreme weather, the wind and parking positions of impeller and inflow directions have been verified as two sensitive factors for aerodynamic loads [24]. Assume a wind turbine impeller at the braking state is within the XOY plane, as shown in Figure 1. The wind direction varies in the XOZ plane with an inflow angle $\beta$. Due to the rapid change of typhoon wind direction, we assume that $\beta \in [0, 90^\circ]$. When $\beta = 0^\circ$, the wind flow direction is perpendicular to impeller surface of the wind turbine.
According to blade element momentum (BEM) theory, the lift force \( dL \) and resistance force \( dD \) for a blade element at angle of attack \( \alpha \) are expressed as [25].

\[
dL = \frac{\rho}{2} C_L(\alpha) V^2 t \tag{1}
\]

\[
dD = \frac{\rho}{2} C_D(\alpha) V^2 t \tag{2}
\]

where \( C_L(\alpha) \) and \( C_D(\alpha) \) are the lift coefficient and resistance coefficient at angle of attack \( \alpha \), respectively, \( \rho \) is the air density, \( t \) is chord length, and \( V \) is the relative wind velocity between wind and the wind turbine speed. For a specific working condition, the lift coefficient \( C_L(\alpha) \) and resistance coefficient \( C_D(\alpha) \) can be determined by angle of attack \( \alpha \).

In general, the relative wind velocity \( V \) is related to the axial and tangential induction factors. When the wind turbine is parked under extreme weather, the induction factors can be neglected. As indicated in Figure 1, the inflow wind velocity \( U \) can be decomposed into \( x \) and \( z \) directions as

\[
U_x = U \sin \beta 
\]

\[
U_z = U \cos \beta 
\]

For a blade element, the inflow velocity is decomposed into \( z_b \) and \( x_b \) directions in the local axis, as shown in Figure 2.
Since the wind turbine is at the braking state, the velocity triangle is expressed as

$$V^2 = \sqrt{V_{zb}^2 + V_{xb}^2}$$  \hspace{1cm} (5)$$

in which $V_{zb} = U_z$, $V_{xb} = U_x \sin \phi$.

From Figure 2, the angle of attack $\alpha$ is [24]

$$\alpha = \tan^{-1}\left( \frac{V_{xb}}{V_{zb}} \right) = \tan^{-1}(\tan \beta \sin \phi)$$  \hspace{1cm} (6)$$

From Equation (6), the angle of attack $\alpha$ is determined by the parking state and the inflow direction. The angle of attack reaches maximum when the blade is parked at $\phi = 90^\circ$, at which parking state the angle of attack $\alpha$ equals the angle of inflow $\beta$. When $\beta = 90^\circ$, the blade is in adverse condition as the resistance force is perpendicular to the blade surface, leading to large bending deformation.

With Equations (1)–(6), the wind load is expressed as the resultant force of lift force and resistance force as

$$dF_{eq} = \sqrt{dL^2 + dD^2}$$  \hspace{1cm} (7)$$

For an offshore wind turbine blade, assume the blade length is $L$ and the maximum chord length is $L_c$. As the section size of blade is much smaller than its length, the wind turbine blade can be treated as a cantilever beam [26]. As shown in Figure 3, the effect of wind load on the blade is expressed in the form of distributed force $q(x_i)(0 \leq x_i \leq L)$.

![Figure 3. Schematic diagram of blade force under wind load.](image-url)

As indicated in Equations (1) and (2), the wind load on the blades varies with angle of attack and chord length. In the following analysis, the wind load $q(x)$ is equivalent to uniformly distributed load $q$ with units $N$ for simplicity. For a cantilever beam structure, the deflection of the blade can be expressed as

$$w(x) = c \left(1 - \cos \frac{\pi x}{2L} \right)(0 \leq x \leq L)$$  \hspace{1cm} (8)$$

Equation (8) agrees with the boundary conditions of the cantilever beam as

$$\begin{align*}
  w(0) &= 0 \\
  w'(0) &= 0 \\
  w''(L) &= 0
\end{align*}$$  \hspace{1cm} (9)$$
According to the virtual work principle, assume that the structure has a virtual displacement \( \delta w_i \), the virtual work of external force and the total virtual deformation work received by the deformed body has a relationship as

\[
\delta W_i - \delta U_i = 0 \quad (10)
\]

where \( \delta W_i \) is the virtual work of external force and \( \delta U_i \) is the total virtual deformation work received by \( i \)th blade

\[
\delta W_i = \int_0^L q_i(x) \delta w_i(x) \, dx \quad (11)
\]

\[
\delta U_i = \int \sigma_x \delta \varepsilon_x \, dV \quad (12)
\]

where \( \sigma_x \) and \( \delta \varepsilon_x \) denote the stress and virtual strain subjected to the virtual displacement \( \delta w_i \).

With Equations (8)–(12), the coefficient \( c \) in Equation (8) can be obtained as

\[
c = \frac{32(\pi - 2)}{\pi^5} \frac{qL^4}{EI} \quad (13)
\]

The maximum bending stress response is located at root of the blade as

\[
\sigma_{\text{max}} = \frac{qL^2}{2W_z} \quad (14)
\]

where \( W_z \) is the bending section coefficient of the beam.

As indicated in Equations (13) and (14), the tip displacement and the maximum stress represent the structure stiffness and the structure strength, respectively. Dangerous section is located at root of the blade. Under extreme typhoon, the wind load is very large and usually accompanied by sudden change of wind direction. In this situation, if either the stress of the blade root \( \sigma_{\text{max}} \) exceeds the allowable stress requirements \([\sigma]\) or the tip displacement \( w_{\text{max}} \) exceeds the allowable deflection \([w]\), the wind turbine blades will face the risk of structural failure.

3. Wind Load Reduction Design

3.1. Structure Strengthening Design of Reinforcing Cable Component (RCC)

When designing the blades for an offshore wind turbine, the power generation efficiency and structural characteristics are equally important. While good power generation efficiency requires large blades with light weight and thin thickness, the structural performance usually relies on the proper layout of blade skin and reinforcements, such as spars. However, the two demands are often contradictory [27]. For example, when less mass is required for larger power generation efficiency, some sacrifices, such as reducing the amount of spars inside the blades, should be taken to reach a compromise. Concerns have thus been raised about structural strength and structural stiffness of blades for large offshore wind turbines, especially in extreme weather. Based on the analysis in Section 2, the extreme wind load on the blade is perpendicular to the blade under extreme weather. The bending resistance property of blades, as well as the structure stiffness, is essential for large offshore wind turbines consequently.

The proposed strengthening structure for offshore wind turbine blades is shown in Figure 4.
The proposed reinforcing cable component (RCC) is composed of three reinforcing cables and the corresponding mechanical connectors. The reinforcing cables are connected to blades at the same location separately through a mechanical connector. The RCC can be viewed as a stay cable, which has advantages of light weight, easy installation, and low cost [28]. As shown in Figure 4, the wind turbine integrated with stay cables is still a symmetrical structure and has no influence on the original pitch system. When the blades suffer stress under wind load, the RCC can enhance the structure ability by providing external tension force, so as to alleviate the structural stress at blade root and to improve the bending resistance performance of blades. In practical engineering, the RCC can be connected to blade through a mechanical sleeve, as shown in Figure 4b.

The wind load reduction mechanism will be analyzed in the next section.

### 3.2. Wind Load Reduction Analysis

The wind load reduction mechanism for blades with RCC is displayed in Figure 5.

The wind load perpendicular to blade surface is expressed in the form of distributed force, which is denoted as $F_i, i = 1, 2, 3$. For the braking state shown in Figure 5, the wind
load on the three blades has the following relationship as $F_2 = F_3 \gg F_1$. In this case, we assume that the deflection of blade 1 can be ignored and the tension force $T_1 = T_2$.

Assume the length of reinforcing cable is $\xi$ and the distance between the connection point between the RCC and the blade root is $x_0 = kL (0 < k \leq 1)$. When the RCC is connected at the same location for each blade, we have $\xi = \sqrt{3}kL$. As shown in Figure 6, the effect of RCC can be decomposed into the tension force $\zeta$ along the blade span direction and the tension force $\theta$ along the blade bending direction as

\begin{align}
\theta &= T \sin \alpha' \\
\zeta &= T \cos \alpha' 
\end{align}

Figure 6. Geometric relationship of the reinforcing cable and blades.

Consider bending deformation, the virtual work of external force can be expressed as

\[ \delta W_\theta = \delta \left( \int_0^L qw_c dx - \theta w_c \right) \]  

(17)

The virtual bending strain energy with RCC can be expressed as

\[ \delta U_\theta = \int_0^L E \left( \int_A y^2 dA \right) \left( \frac{d^2 w_\theta}{dx^2} \right) \left( \frac{d^2 \delta w_\theta}{dx^2} \right) dx \]  

(18)

The assumed displacement of the blade is consistent with Equation (8) as

\[ w_\theta = c_\theta \left( 1 - \cos \frac{\pi x}{2L} \right) \]  

(19)

According to the principle of virtual work [29],

\[ \delta W_\theta - \delta U_\theta = 0 \]  

(20)
The unknown parameter in Equation (19) can be obtained as

\[ c_\theta = \frac{32(\pi - 2)}{\pi^3} \left( \frac{L^4 p}{EI} \right) - \frac{32L^3}{EI\pi^4} \left( 1 - \cos \frac{k\pi}{2} \right) \left( 0 \leq k \leq 1 \right) \]  

(21)

The relationship between the elongation of the reinforcing cable \( \Delta \xi \) and the deflection of blade 2 \( w_\theta \) is displayed in Figure 6. According to the small deformation assumption of the beam, the complementary Equations are obtained by geometric relations under local coordinate system as

\[ (\xi + \Delta \xi) \sin \alpha_2' = w_\theta + \frac{\xi}{2} \]  

(22)

\[ (\xi + \Delta \xi) \cos \alpha_2' = \frac{3}{2} kL (0 \leq k \leq 1) \]  

(23)

The tension force of RCC is denoted as \( T = E_s \Delta \xi \), where \( E_s \) denotes the Young’s modulus. With Equations (19), (21) and (23), the tension force \( T \) of RCC can be derived.

After applying the RCC, the stress at the root of the blade is reduced to

\[ \sigma_{RCC} = \frac{1}{W_z} \left( \frac{q x_0^2}{2} - T \sin \alpha_2' x_0 + T \cos \alpha_2' w_\theta \right) \approx \sigma_{\text{max}} - \frac{T \sin \alpha_2' x_0}{W_z} \]  

(24)

From the above analysis, the deflection \( w_\theta \) is much smaller than \( x_0 \), and \( \alpha_2' \) is slightly larger than the angle \( \alpha_2 = \frac{\pi}{6} \); thus, in Equation (24), the third term on the right side of the Equation is much smaller than the second term. As the original cantilever boundary condition of wind turbine blade is altered by RCC, the stress on the blade is reduced.

Due to the complex shape of wind turbine blade, the wind loads are not normally uniformly distributed, leading to the exact theoretical solution of stress distribution is difficult to obtain. In the next section, the offshore wind turbine blade will be accurately modeled and the stress and strain distribution of the blade with and without the connection of RCC will be studied through Finite Element (FE) simulation.

4. Simulation Results from FE Models

4.1. Wind Turbine Blade Model

In this paper, a full-scaled 5 MW wind turbine blade of the US National Renewable Energy Laboratory (NREL) is adopted to establish the blade model. The blade is divided into 19 sections along the length during modelling. The main geometric features of the 5 MW wind turbine blade are listed in Table 1.

| Section Number | Distance to Blade Root/m | Chord Length/m | Twist Angle/° | AIRFOIL TYPE |
|----------------|--------------------------|----------------|---------------|--------------|
| s1             | 0                        | 3.20           | 13.308        | Cylinder     |
| s2             | 1.36                     | 3.54           | 13.308        | Cylinder     |
| s3             | 4.1                      | 3.85           | 13.308        | Cylinder     |
| s4             | 6.83                     | 4.17           | 13.308        | DU40_A17     |
| ...            | ...                      | ...            | ...           | ...          |
| s9             | 26.25                    | 3.75           | 6.544         | DU25_A17     |
| s10            | 30.75                    | 3.50           | 5.361         | DU21_A17     |
| ...            | ...                      | ...            | ...           | ...          |
| s18            | 60.13                    | 1.40           | 0.370         | NACA64_A17   |
| s19            | 61.5                     | 0.70           | 0.106         | NACA64_A17   |

The fiber composite materials are adopted for the 5 MW offshore wind turbine blades. The material parameters are referred to reference [31]. The composed composite material is a sandwich structure with glass fiber and carbon fiber fabric sequentially covering the upside
and downside of the PVC foam core. Each layer of the fiber has a thickness of $2.8 \times 10^{-4}$ m and a maximum layer of 80 and 20 are set for glass fiber and carbon fiber separately.

The section area of RCC is set as $3 \times 10^{-4}$ m$^2$. Length of RCC is related to the connecting location on the blade with a relationship of $\xi = \sqrt{3kL}$. The structural steel material is adopted for RCC, as displayed in Table 2.

Table 2. Material parameters of RCC.

| Material Parameters | Young’s Modulus | Density | Poisson’s Ratio |
|---------------------|-----------------|---------|----------------|
| RCC                 | $2.16 \times 10^{11}$ Pa | 7800 kg/m$^3$ | 0.28 |

The geometry model of wind turbine blade is firstly established with 3D modelling software (CATIA V5 R20, Dassault Systems, Paris, France) and then imported into the Finite Element software COMSOL Multiphysics for FE analysis. The wind turbine blade model is decentralized into 17089 shell elements, 7333 solid elements, and 120 line elements, as shown in Figure 7.

![Figure 7. The FE model of wind turbine blade and applied load; (a) FE mesh of the total model; (b) Local enlarged view of FE mesh.](image)

The boundary conditions and applied loads on wind turbine blades are displayed in Figure 8.

![Figure 8. Boundary conditions of the wind turbine rotor.](image)

As shown in Figure 8, a fixed boundary condition is applied at the hub to simulate the braking status of the wind turbine and the distributed equivalent aerodynamic force are
applied to each section [32]. With Equations (1)–(7), the resultant force of blade segments under the extreme wind velocity of 60 m/s are calculated and displayed in Table 3. As the blade has circular sections at root of the blade, the aerodynamic load is calculated from Section S4 to Section S18.

Table 3. Aerodynamic load under extreme condition.

| Section Number | Distance from Section to Blade Root /m | Equivalent Resultant Force /N |
|----------------|---------------------------------------|-----------------------------|
|                |                                       | Blade 1 | Blade 2 | Blade 3 |
| S4             | 10.25                                 | 13,981.31 | 10,485.98 | 10,485.98 |
| S5             | 14.35                                 | 14,396.55 | 10,797.41 | 10,797.41 |
| S6             | 18.45                                 | 13,796.18 | 10,347.13 | 10,347.13 |
| S7             | 22.55                                 | 13,163.37 | 9872.53  | 9872.53  |
| S8             | 26.65                                 | 12,413.66 | 9310.24  | 9310.24  |
| S9             | 30.75                                 | 11,611.28 | 8708.46  | 8708.46  |
| S10            | 34.85                                 | 11,185.51 | 8389.13  | 8389.13  |
| S11            | 38.95                                 | 10,399.77 | 7799.83  | 7799.83  |
| S12            | 43.05                                 | 9620.90  | 7215.67  | 7215.67  |
| S13            | 47.15                                 | 8834.61  | 6625.96  | 6625.96  |
| S14            | 51.25                                 | 8048.31  | 6036.24  | 6036.24  |
| S15            | 54.67                                 | 7393.07  | 5544.80  | 5544.80  |
| S16            | 57.4                                  | 6667.51  | 5000.63  | 5000.63  |
| S17            | 60.13                                 | 4474.84  | 3356.13  | 3356.13  |
| S18            | 61.5                                  | 2237.42  | 1678.06  | 1678.06  |

4.2. Results and Discussion

To find the influence of the RCC location on blade stress response, a series of finite-element analyses are conducted using COMSOL Multiphysics software. The FE models of wind turbine with and without the reinforcing structure are analyzed separately. The connecting point of reinforcing cable is set from one third of the blade length to the blade tip along the spanwise direction. The corresponding Von Mises stress response of blade 1 is displayed in Figure 9.
According to the FEM results, the blades without RCC has the largest stress at the junction between the circular and airfoil cross sections. The large stress area is relieved when the RCC is applied. Meanwhile, one can also notice that the local stress concentration appearing at the connection point of reinforcing cable. This is due to the discontinuity of blade geometry at the connection point. The maximum stress is further decreased when the RCC is connected at two-thirds of the blade length. By comparing Figure 9a–d, the stress of the connecting point is less than the other two situations. The stress close to root of the blade is significantly reduced after applying the RCC, which demonstrates that anti-bending performance of the structure is improved. When the connecting point is removed to the blade tip, as shown in Figure 9e, the stress response of the whole blade is much lower. However, it should be noticed that the maximum stress of the whole structure reaches $1.79 \times 10^9$ N/m² when the RCC is connected at the blade tip, which is second only to blades without RCC.

The stress distribution on the blade surface for different RCC connecting positions are compared in Figure 10.

The stress response is reduced to varying degrees for the distance less than 14.35 m. When the RCC is connected to $L/3$ of the blade length, the stress response is increased at 18.45 m and 26.65 m, more than 23% of the maximum stress value without RCC. The stress increase phenomenon is relieved with the movement of RCC. When the RCC connecting point is moved to $L/2$ of the blade length, the stress at 26.65 m and 38.95 m is increased and is almost equal to the original maximum value. When the RCC is connected at $2L/3$ of the blade length, the stress is only slightly increased at 51.25 m, far less than the maximum
stress value of blades without RCC. Although an obvious decrease of the overall stress can be seen when the RCC is connected at the blade tip, the stress at 57.4 m is far greater than the largest stress of blades without RCC. The concentration of stress is likely to produce fatigue cracks on the blade surface, leading to severe accident without timely maintenance. Therefore, we can conclude that the optimal connecting position for RCC is at $2L/3$ of the blade length.

Table 4 summarizes the maximum displacement at blade tip of the two wind turbine blade models.

**Table 4.** Tip displacement response of blades.

| Blade Type | Blade 1 without RCC | Blade 1 with RCC at $2L/3$ | Blade 2 without RCC | Blade 2 with RCC at $2L/3$ | Blade 3 without RCC | Blade 3 with RCC at $2L/3$ |
|------------|---------------------|---------------------------|---------------------|---------------------------|---------------------|---------------------------|
| Tip displacement /m | 7.04                | 5.13                      | 6.78                | 1.49                      | 6.74                | 2.61                      |

As discussed above, the wind load is directly related to the position of the blade. As blade 1 is perpendicular to the incoming flow direction, the relative wind velocity is higher than the other two blades. Therefore, blade 1 has the largest tip displacement among the 3 blades. The proposed RCC effectively reduces the maximum displacement of the blade tip, with 27.1% for blade 1 and more than 50% for blade 2 and blade 3, thus the structure stiffness of the wind turbine blades is improved.

Figure 11 presents the overall strain distribution of wind turbine blades without and with RCC at $2L/3$ respectively. The strain reduction trend is similar to that of stress. The strain close to root of the blade is reduced obviously for all blades, implying the load reduction effect of the RCC. The strain at connecting point is slightly increased, but it has no influence on the overall reduction effect when the RCC is connected at the optimal location. The maximum strain of blades with RCC is reduced to half of the blades without RCC.

![Figure 11. Blade strain comparison: (a) Blade without RCC; (b) Blade with RCC connected at $2L/3$.](image)

The stress response of RCC is displayed in Figure 12. When the wind direction is parallel with rotor surface, only two of reinforcing cables are in tension.
As shown in Figure 12, the stresses of the two reinforcing cables are $5.09 \times 10^8$ N/m$^2$ and $7.24 \times 10^7$ N/m$^2$, respectively. As the maximum stress of RCC is within the material tensile strength $5.50 \times 10^8$ N/m$^2$ [33], the RCC is able to reduce external load for blades under extreme weather safely.

5. Static Load Strain Test

5.1. Test Description

To verify the load reduction effect of RCC, a small-sized wind turbine blade with a length of 0.8 m is adopted for test, as shown in Figure 13. The test blade is made of nylon fiber. To simulate the stress situation under extreme weather, the fan blades are installed according to the feathering state. Each root of blades is fixed on a hub without rotation. The strain on the blade is firstly captured by several rectangular rosettes, and then recorded by a static strain gauge.

In static testing, different types of loads correspond to tests for different purposes [34]. The load is assumed to be parallel with the flap-wise direction, which corresponds to extreme conditions of wind load. In this test, mass load [35] (4.9 N) is adopted to test the strength of blade with RCC. The mass load is suspended at the blade tip.

Several BX120-3CA rectangular rosettes are pasted along the blade span direction, as displayed in Figure 14. The rectangular rosettes can be used to measure the strain of tested structure at 0, 45, and 90 degrees simultaneously.
Figure 14. Diagram of strain measuring point on the blade.

The serial numbers of the rectangular rosettes increase from the blade root to the blade tip, that is, with No. 1 as the measuring point near the blade root and No. 8 as the measuring point close to the blade tip. Based on simulation results, the connecting point of the RCC on the blade is two-thirds of total length of the blade from the blade root.

The main experimental steps are as follows: The static strain of blade without loading is firstly measured by the static strain gauge, and the static strain without loading at all eight measuring points are recorded. Then, a mass of 4.9 N is hung on the blade tip, meanwhile the static strain with loading at all eight measuring points are recorded, respectively. To ensure the reliability of test results, each loading and recording procedure are repeated three times during the test. The recording results are averaged to reduce the test error.

5.2. Load Reduction Effect Discussion

The principal strain is calculated as follows.

$$\epsilon_{\text{max}} = \frac{\epsilon_{90} + \epsilon_0}{2} + \sqrt{\left(\frac{\epsilon_{90} - \epsilon_0}{2}\right)^2 + \left(\frac{\epsilon_{90} + \epsilon_0 - 2\epsilon_{45}}{2}\right)^2}$$  \hspace{1cm} (25)

where $\epsilon_0$ represents the strain in the axis direction, $\epsilon_{90}$ represents the strain with an angle of 90° to the horizontal axis, and $\epsilon_{45}$ represents the strain with an angle of 45° to the horizontal axis.

Reduction percentage of average strain at measuring point $i$ is defined as

$$B_i = \frac{\epsilon_{0i} - \epsilon_{1i}}{\epsilon_{0i}}$$  \hspace{1cm} (26)

with $\epsilon_{0i}$ and $\epsilon_{1i}$ representing the average strain at measuring point $i$ before and after applying the RCC.

The measured strain results of each measuring point on the blade are displayed in Table 5.

| Measuring point | Average Strain Without Reinforcing Cable Component | Average Strain With Reinforcing Cable Component | B% |
|----------------|---------------------------------------------------|-----------------------------------------------|----|
| Measuring point 1 | 178.16                                           | 34.45                                         | 80.7% |
| Measuring point 2 | 176.26                                           | 47.59                                         | 73.0% |
| Measuring point 3 | 349.32                                           | 132.72                                        | 62.0% |
| Measuring point 4 | 221.06                                           | 91.13                                         | 58.8% |
| Measuring point 5 | 160.90                                           | 89.14                                         | 44.6% |
| Measuring point 6 | 161.55                                           | 167.46                                        | -3.7% |
| Measuring point 7 | 177.03                                           | 156.31                                        | 11.7% |
| Measuring point 8 | 97.30                                            | 105.77                                        | -8.7% |

As shown in Table 5, the maximum strain for blades without RCC occurs at the measuring point 3, where the blade shape changes greatly. After applying the RCC, the
reduction percentage of the average strain reached 62.0%, indicating a good load reduction effect for a dangerous section. The strain response of the test blade is reduced at different levels except for measuring point 6 and measuring point 8. For the measuring point 1 which is close to root of the blade, 80.7% strain is reduced by RCC. The strain at the blade root is also effectively relieved.

Only the strain at measuring point 6 and measuring point 8 is slightly increased. The reason can be explained as follows. As shown in Figure 14, the measuring point 6 is close to the connection point of RCC. When the blade is connected with RCC, the area near the connecting point forms a discontinuity area, which is subject to both the external load and the tension of the cable simultaneously. As the connection area is small, the induced stress is enlarged. For measuring point eight, the reason is similar. The strain is increased as the mass is hung at the blade tip through a steel cable. This will not happen since the wind load acts on the whole blade surface in actual situation, as one can see that the strain does not increase at the blade tip in the simulation result.

6. Conclusions

Under extreme weather, the angle of wind turbine surface and blades must be adjusted continuously according to the inflow direction to protect the blades from breaking. Untimely adjustment may lead to structure failure at blade root. In this paper, the bending resistance ability of wind turbine blade was improved by a novel mechanical design. The main conclusions can be drawn as follows: (1) A reinforcing cable component (RCC) was proposed to reduce wind load on blade. To gain better reduction of load, the connection point of RCC is suggested to be located at two-thirds of the blade length. (2) The proposed RCC improved stress distribution by altering the cantilever boundary condition of wind turbine blades. According to finite element results, the large stress at the root as well as tip placement were effectively decreased. (3) A static strain test for a small-scaled wind turbine indicated good load reduction effect of RCC, 80.7% strain was reduced at the blade root. The proposed RCC has no limitations of braking position and blade angle, which contributes to improve the survivability of wind turbines under extreme weather.

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Nomenclature

\( \alpha \) Angle of attack (°)
\( \beta \) Wind direction (°)
\( \phi \) Blade parking angle (°)
\( V \) Relative wind velocity (m/s)
\( t \) Chord length (m)
\( L \) Blade length (m)
\( w \) Deflection of blade (m)
\( \xi \) Length of RCC (m)
\( \Delta \xi \) Elongation of RCC (m)
\( W_c \) Bending section coefficient (m³)
\( F_i \), \( i = 1, 2, 3 \) Distributed wind load (N)
\( q \) Distributed force (N)
\( T \) Tension force (N)
\( \sigma \) stress (N/m²)
\( E_s \) Young’s modulus (Pa)
\( \varepsilon_0 \) Strain in the axis direction
\( \varepsilon_{45} \) Strain with an angle of 45° to the horizontal axis
\( \varepsilon_{0i} \) Average strain at measuring point \( i \) before applying RCC
\( \varepsilon_{1i} \) Average strain at measuring point \( i \) after applying RCC
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