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Review

Typhoon Resistance Analysis of Offshore Wind Turbines: A Review

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Abstract: A typhoon is a tropical cyclone in the western Pacific Ocean and the China seas. Typhoons are some of the most destructive natural disasters on Earth. In China, typhoons have had major impacts on the stability and structural integrity of offshore wind turbines in the complex and harsh marine environment. In this research, first, the main causes of wind turbine damage were analyzed based on the characteristics of a typhoon and a wind turbine structure for typical typhoon-induced accidents. Second, the research progress of the anti-typhoon design of offshore wind turbines and the anti-typhoon strategy of wind farms operation and maintenance was summarized. Finally, the problems to be further solved in these research fields were presented to provide references for the development of offshore wind turbines, in particular, floating wind turbines in typhoon-prone areas.

Keywords: offshore wind turbine; structural damage; typhoon resistance design and strategy

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1. Introduction

As an emerging renewable energy industry, offshore wind energy has gradually become an important supplement to fossil fuel due to its great utilization potential, high-level resources, and stable output [1,2]. Through technology innovations and scale production, the competitive advantage of wind power continues to build throughout the world. According to the Global Wind Report 2021 [3], total offshore wind capacity has now passed 35 GW, representing 4.8% of the total global cumulative wind capacity. In 2020, the offshore wind power industry added 6.1 GW of new installations worldwide. China, as a major force in the global offshore wind market, accounted for half of all new global offshore wind installations in this record year. To reach the targets of carbon peaking before 2030 and carbon neutrality by 2060 established by the Chinese government, accelerating the development and utilization of offshore wind energy has become imperative for accelerating the energy transition, tackling climate change, and achieving low carbon emission reduction.

China is rich in offshore wind energy resources. According to the assessment conducted by the China Meteorological Administration, the offshore wind energy at water depths of 5–25 m is approximately 200 GW, and the offshore wind energy at water depths of 5–50 m is approximately 500 GW. With the increasing ceiling for shallow-water wind development, the development of long-distance deep water offshore wind is planned. The advantages of a deep-sea location over offshore shallow water are prominent: the steady and strong deep-sea winds generate more electricity and do not affect the operation of shallow water fishing, aquaculture, or other related industries [4]. Nevertheless, the geotechnical conditions of the seabed in different parts of China vary considerably, from soft clays to hard rock, requiring a greater variety of piling techniques [5]. Therefore, it is more necessary for China to actively explore and reserve technologies in the field of deep water floating wind power. At present, floating wind turbines have become the most active field of international wind technological innovation. According to the Carbon Trust's

Second Phase Summary Report on the Floating Wind Combined Industry Project [6], global floating wind power is expected to increase by 10.7 GW by 2030. By 2040, 70 GW of floating offshore wind power is expected to be installed worldwide.

However, many uncertain risk factors produced by complex and harsh marine environmental conditions pose great challenges to the development and utilization of wind power and the operation and maintenance of wind turbines in China. Compared with onshore wind energy, offshore wind turbines are more susceptible to extreme weather, such as typhoons [7]. Most of the severe typhoons in the world are generated in the Pacific Ocean, and gradually strengthen in the process of moving toward the north, northwest, west, or northeast directions. The northwest Pacific Ocean has the highest frequency of typhoons in the world, and China has the most typhoons landing in the world [8]. Typhoons can induce strong wind, heavy rain, huge waves, and storm surges. The intense effects of typhoons significantly increase the vulnerability of coastal cities and constructions, which has become one of the most important control factors for the safety and applicability of engineering structures. Therefore, typhoons have become the main and unique environmental factor restricting the development of China's offshore wind power [9]. The innovation in typhoon resistance has increased in recent years. With this background, first, this study introduces the damage to the wind farms in China from typhoons. Second, the failure modes of each component of the wind turbine are analyzed based on the typical typhoon-induced failure events. Then, the anti-typhoon research on different wind turbine components and the strategy of the operation and maintenance of wind farms are reviewed. Finally, research advances and the problems in the field are presented. The purpose of this study is to provide some references and suggestions for anti-typhoon research for offshore wind power in typhoon-prone areas.

2. Impacts of Typhoons

A typhoon is a mesoscale atmospheric vortex system in the western Pacific Ocean and China seas. A typhoon has winds measuring greater than 32.7 m/s. According to the national classification of the tropical cyclones of China (GBT 19201-2006) [10] shown in Table 1, tropical cyclones are classified as follows. (1) Because the cut-off speed of an offshore wind turbine is 25 m/s, a low-grade tropical cyclone, that is, a tropical depression (TD) or tropical storm (TS), can result in additional power generation for wind turbines; thus, this type of cyclone is categorized as an "economic tropical cyclone." (2) For a severe tropical storm (STS), wind turbines should be parked and defended, so an STS is called a "defensive tropical cyclone." (3) Once a tropical cyclone intensifies into a typhoon (TY), severe typhoon (STY), or super typhoon (Super TY), it will produce the devastating destruction of wind turbines, so this type of cyclone is classified as a "destructive tropical cyclone."

Table 1. Classification of tropical cyclones.

Classification	Wind Speed	Wind Strength
Tropical depression (TD)	10.8–17.1	6–7
Tropical storm (TS)	17.2–24.4	8–9
Severe tropical storm (STS)	24.5–32.6	10–11
Typhoon (TY)	32.7–41.4	12–13
Severe typhoon (STY)	41.5–50.9	14–15
Super typhoon (Super TY)	51.0 or higher	16 or higher

China is hit by typhoons with great frequency each year. Along the coastalline of nearly 20,000 km in China, the provinces with the most wind energy resources are all located in the active typhoon region [11]. The most vulnerable coastal areas for super typhoons are Guangdong, followed by Hainan Taiwan, Zhejiang, and Fujian [8]. Typhoons threaten the stability and structural integrity of offshore wind turbines with events such as serious blade damage, tower collapse, and foundation overturning [12]. China's coastal wind farms are repeatedly struck by typhoons, resulting in huge economic losses. Wind turbines in coastal wind farms have suffered particularly severe structural failures due to typhoons, as shown in Table 2.

Table 2. Structural failures of wind turbines caused by typhoons in recent years.

Year	Typhoon	Wind Farm/Province	Main Failure Modes
2003	Dujuan	Honghaiwan/Guangdong	Blade damage, 9
2006	Saomai	Hedingshan/Zhejiang	Blade damage, 15 Tower collapse, 3 Foundation overturned, 2
2010	Megi	Liuao/Fujian	Blade damage, 1 Tower collapse, 1
2013	Usagi	Honghaiwan/Guangdong	Blade damage, 11 Tower collapse, 8
2014	Rammasun	Warriors/Guangdong	Blade damage, 15 Tower collapse, 13
2014	Rammasun	Wenchang/Hainan	Blade damage, 2 Tower collapse, 1
2018	Maria	Dajing/Fujian	Tower collapse, 1 Blade damage, 1
2018	Maria	Lvxia/Fujian	Tower collapse, 1

The damage to offshore wind turbines due to typhoons is mainly attributed to three characteristics of a typhoon [13]. The first characteristic is extreme wind speed. A typhoon is a low-pressure system. With the action of horizontal pressure, the external airflow blows to the typhoon center from all sides. Due to the effect of the Earth's rotation in the north of the equator, the airflow involved rotates counterclockwise, and the more the airflow spins into the typhoon, the greater the tangential wind speed is. In the area where the typhoon passes, the pressure curve is funnel shaped. With the sharp drop and rise in the pressure, the wind direction changes from northeast to south and southwest. The closer the center of a typhoon, the greater the wind speed. The wind speed drops sharply as the eye passes, then increases again 10 min to 30 min later (depending on the size and speed of the eye), and slowly decreases as the typhoon moves away. The most intense and concentrated area of a typhoon is the cloud wall area, with a width of 10–20 km at the edge of the eye, as shown in Figure 1. Usually, the north wind speed is the strongest at the moment before the eye of a typhoon arrives. The wind load acting on the wind turbine is proportional to the square of the wind speed. Once the wind speed is greater than the designed limit of the wind turbine, some accidents may occur. The second characteristic is the sharp change in the wind direction. When the typhoon center passes through, the angle of the wind direction changes by more than 45° in a short time (less than 6 h), and the wind near the center will even change by 120–180°. For a wind turbine that has been shut down and feathered, the sudden change of the wind direction means that the main wind direction shifts from the front of the wind motor to the side and rear, and the wind area changes accordingly. The third characteristic is the dramatic turbulence intensity. The turbulence intensity is the ratio of the standard deviation of the turbulent wind speed in 10 min to the mean wind speed in the same period, which reflects the amplitude of the random variation of the wind speed. The turbulence intensity in the process of the typhoon has unique characteristics that are related to the distance from the typhoon center. The closer the distance is to the typhoon center, the more the abnormal turbulence phenomena that occur. Strong turbulence will force the rotor mechanism of the wind turbine to vibrate randomly, which will cause serious damage.

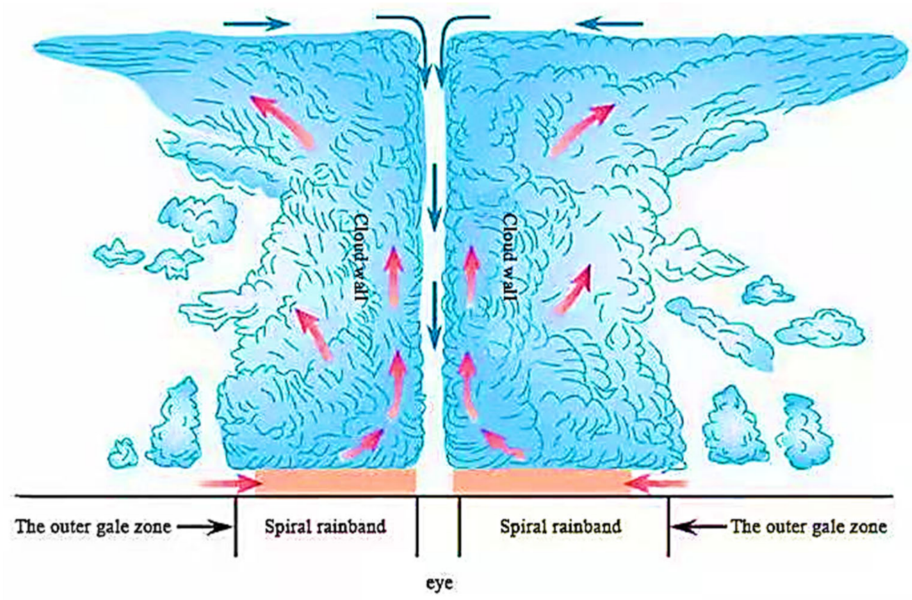


Figure 1. Structure of a typhoon.

Field measurement [14,15] and numerical simulation [16,17] are the common approaches to investigate the typhoon wind characteristics, such as wind profile, gust factor, mean velocity, turbulence intensity and scale, spatial correlation and coherence, probability density function, power spectrum, and so on. The conventional wind tunnel test is another approach; however, it is difficult to accurately simulate the characteristic of typhoons [18]. The numerical simulation is flexible and efficient. However, the results are sensitive to the user-defined computational parameters, the setting of boundary conditions, and the reliability of numerical codes. In addition, the simulation results need to be validated by the field measurements [19]. So far, the field measurement is considered to be the direct and reliable solution for obtaining the typhoon wind characteristics [20].

Furthermore, the devastating impacts of typhoons on offshore wind turbines are due not only to wind power, but also to the superimposed coupling effect of large waves caused by typhoons. In the initial stage of a typhoon, although there is a large wind speed on the surface of the sea, the wave height is not high. At this stage of development, the wave height also increases with the increase in the typhoon wind speed. When the typhoon reaches the mature stage, the wind speed no longer increases, and the range of strong wind gradually expands outward. In this stage, the wave height is also grown sufficiently, while the scope of the giant wave region is expanded to the speriphery of the typhoon. When the typhoon weakens, the wind speed decreases, but the sea area affected by the typhoon still has a large wave height. Eighty percent of the typhoons affecting China can form a large wave with a height greater than 6 m [21]. Therefore, it is necessary to investigate the motion response of offshore wind turbine foundations induced by typhoon waves. The current data show that the typhoon wind data are adequate, and the simulation methods of a typhoon wind field are relatively mature. However, the research on the environmental parameters and characteristics of typhoon waves is not comprehensive. In particular, long-term wave data about the southeastern coast of China are lacking.

3. Failure Mechanism and Typhoon Resistance Design of Offshore Wind Turbine

An offshore wind turbine is a typical "top-heavy" structure, which has the characteristics of a flexible–rigid coupling, small damping, and weak vibration resistance. The structural components of an offshore wind turbine are mainly categorized into the five parts shown in Figure 2: blade, hub, nacelle, tower, and foundation [22]. Most wind turbines have three blades. The size of the blades determines the power capacity of a wind turbine. Blades are connected to the hub and can rotate the blade pitch angle using the pitch system in the hub. The nacelle is the protection of the core parts of the turbine, such as the generator, gearbox, drive train, shafts, and control systems. The tower sits on a supporting foundation and holds the weight of the turbine.

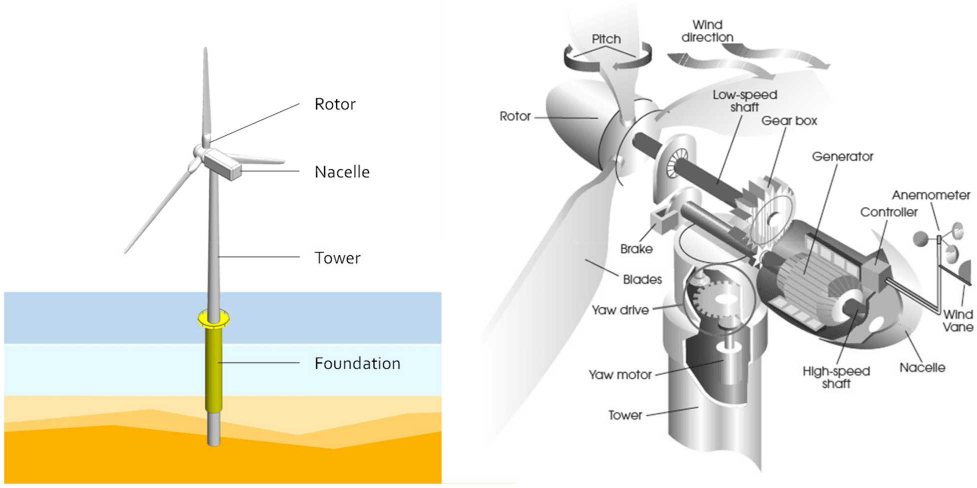


Figure 2. Components of an offshore wind turbine.

3.1. Blade

3.1.1. Failure Mechanism

The blade structure is generally formed by bonding the upper and lower shells with specific airfoil and the blade beams bearing the main bending stress. Compared with the foundation and the tower, the blade is the weakest part of a wind turbine, and also the vulnerable part in typhoon conditions. When a typhoon occurs, the wind turbine stops working, and the rotor speed is zero. Even if the blade can reduce the aerodynamic loads through the pitch system, damage is always inevitable, ranging from noise pollution and aerodynamic performance decreases to cracking or even fracturing.

The on-site photographs of the Honghaiwan wind farm (as shown in Figure 3) show that super Typhoon Usagi caused the fracture at the load-carrying box beam of the blades. Eleven blades of eight wind turbines were broken, and the blade azimuths of the damaged wind turbines differed. In addition, there was no obvious crack near the damaged side of the blade. The estimated maximum wind speed was 75.8 m/s during Typhoon Usagi, which exceeded the design criterion. Thus, the main failure mode was a complete fracture [23]. During Typhoon Dujuan, the maximum instantaneous wind speed measured by the wind turbine was 57 m/s, which was far lower than the designed wind of 70 m/s. However, nine blades were damaged to different degrees. The failure was mainly due to the varying wind direction. When the wind turbine entered the shutdown state, the yaw system stopped working. After that, as the wind direction continued to change, the angle of attack on the fixed rotor blades became larger. At the same time, the wind speed further increased, resulting in some blades being completely damaged and entering a state of severe torsional flutter. With the coupling action of the torque, shear force, and bending moment, the blade with insufficient torsional stiffness was buffeted by strong turbulence [24]. Similarly, the wind turbines in the Changhua wind farm were able to withstand sustained wind speeds above 70 m/s. However, seven blades were damaged by Typhoon Jangmi with the maximum instantaneous wind speed of approximately 53.4 m/s. The blade damage mainly resulted from the wing edge vibrations caused by vortexes through the local resonance effect [25]. When Typhoon Megi hit the Liuao wind farm, the turbulence intensity was over 0.3 and the inflow angle was over 20°. Both of these values exceeded the design limits [26]. Through the analysis of typical accidents, it can be seen that the aerodynamic load caused by typhoons exceeds the design load of blades, which leads to blade failure. Furthermore, with the development of large-scale wind turbines, the size of the blade increases accordingly. The deflection under typhoon conditions will be greatly enlarged.

The traditional static simulation method for wind loads may underestimate the typhoon impacts on blades. Therefore, typhoon resistance research on blades should focus on accurate and efficient aerodynamic analysis tools.

Figure 3. Photograph showing blade damage due to Typhoon Usagi [23].

3.1.2. Simulation of Typhoon Aerodynamic Load

The blade element momentum (BEM) theory is generally used to study the aerodynamic load of wind turbines. All of the current design tools, such as OpenFAST [27], Bladed [28], HAWC2 [29], and OrcaFlex [30], employ the BEM theory for the calculation of the aerodynamic loads on a rotor. Ren et al. [31] chose the representative truncated observation data for Typhoon Damrey to study the aerodynamic characteristics of offshore wind turbine blades based on BEM theory. The results revealed that rapid wind speed change easily caused the time lag of the variable speed and the collective pitch control system. Due to the fluctuations in the wind speed and the direction of typhoons, some scholars have carried out research based on the computational fluid dynamics (CFD) method to simulate typhoon wind loads. Ren et al. [32] studied the influence of the different blade pitch angles and wind directions of typhoons on the aerodynamic loads of wind turbine blades based on the CFD method, and they revealed the most unfavorable blade position and the corresponding blade wind load coefficient with the impacts of typhoons. Yang et al. [33] studied the characteristics of the aerodynamic loads acting on a wind turbine due to gusts during Typhoon Jangmi. They suggested conducting an analysis of an idling wind turbine under gust conditions in the typhoon-prone regions. Lian et al. [34] numerically simulated the aerodynamic loads on blades with different wind directions based on the CFD method, with consideration of the shutdown of the yaw system during a typhoon. Chen et al. [12] calculated the local mean wind profiles at each turbine site using three-dimensional CFD calculation considering the terrain topography of a wind farm reconstructed from global positioning system (GPS) data.

The turbulence intensity and the turbulence integral scale in the whole process of a typhoon from landing to departure are different [35]. Based on the measured data and with consideration of the different characteristics of the typhoon transit process, Han et al. [36] used the measured power spectrum and inverse Fourier transform to generate the fluctuating wind field. Wang et al. [37] established a wind field simulation method for the whole process of typhoon transit for a wind turbine and then used the spectral decomposition method and the improved blade element momentum theory method to calculate the wind load of a wind turbine.

Since it is difficult for micro-scale CFD technology to reflect the complexity of typhoon wind fields [38], mesoscale models, such as weather research and forecasting (WRF) were applied to the study of typhoon wind turbines. These models can not only simulate the wind speed, pressure, and temperature of a typhoon wind field, but also account for the development process of a typhoon. However, because the typhoon range is usually several hundred kilometers, the wind grid resolution is usually at the level of kilometers, but the scale of the whole wind turbine system is only at the level of 100 m. Moreover, the mesh size at the near-wall surface is usually at the millimeter level [39]. To accurately predict the aerodynamic load on a wind turbine blade, it is necessary to combine the micro-scale CFD method with a mesoscale model and to nest a small-scale wind field in the wind field model. Ke et al. [40] proposed to use the WRF model to simulate typhoon "Nuri" and fit the near-surface wind profile. A CFD model was used to simulate the flow field around the wind turbine to analyze the aerodynamic response of the wind turbine with a typhoon load.

In summary, the failure frequency of blades is the highest during typhoons. Blades should not only have enough strength and stiffness to avoid fracture failure and shape change under aerodynamic load, but also have enough stability to avoid natural resonance. At present, in terms of the simulation of the wind loads on blades, the selection of environmental conditions is mostly based on the annual extremum sampling method. The simple selection of environmental parameters often results in either low design standards, leading to the failure and destruction of structures under extreme sea conditions or unnecessary resource waste due to design standards being too conservative. Considering the characteristics of typhoons, the CFD method is needed to accurately calculate the load. In addition, the aerodynamic characteristics of a typhoon in transit are different, so it is necessary to consider the characteristics of different stages to simulate the wind field. However, the CFD method is extremely demanding in terms of computational resources. The diameter of the wind wheel of a modern wind turbine has reached more than 100 m, while the scale of the boundary layer on the blades is at the millimeter level. In addition, the short-term prediction of the dynamic response of a wind turbine (the simulation time needs to be more than 1 h) is required for the passage of typhoons, resulting in a large amount of CFD calculation and a long calculation cycle. Therefore, it is necessary to study efficient and accurate typhoon aerodynamic load simulation methods.

3.2. Tower

3.2.1. Failure Mechanism

A tower is a typical high-rise structure. The shear force and bending moment at the root are the largest. Usually, tower failures occur at the lower parts of a tower. The bearing load is similar to the supporting foundation, but its stiffness is far less. Therefore, a tower has relatively weak typhoon resistance.

The failure modes of tower collapse include excessive deformation, fatigue, fracture, yielding, and plastic collapse [41]. When the load reaches the design limit, plastic deformation will occur. It was observed from the field data of Typhoon Usagi passing the Honghaiwan wind farm that (as shown in Figure 4) the tower was partially in the shape of internal collapse, and the edge of the fold was torn. Most of the bolts connecting the foundation ring were pulled off. The main failure mode was local inelastic buckling, due to steel yielding. The failure position of the tower was between 0.2 and 0.22 of the tower height, and the change in the wall thickness at this position led to the collapse of the tower [42]. Similarly, in the Hedingshan wind farm hit by Typhoon Saomai, one of the collapsed towers buckled at the welded joint of the tower cylinders where the flanges were distorted and the bolts were dragged out [13]. In addition, under extreme wind conditions, the wind direction may change to the crosswind when a typhoon passes through a wind farm, which has an important influence on tower stress. One of the damaged towers during Typhoon Jangmi resulted from the crosswind actions, such as vortex shedding and wake galloping [43].

(**a**) (**b**)

Figure 4. Photographs displaying tower damage due to Typhoon Usagi [23]: (**a**) tower collapse; (**b**) buckling failure.

3.2.2. Typhoon Resistance Structural Analysis

The structural analysis of a tower is often conducted based on the finite element method (FEM). Because of the installation of the heavy rotor and nacelle, a tower should be considered a flexible structure, and its deformation should be simulated. A tower is modeled as a thin-walled cylinder with variable cross sections. According to the material properties and cross-sectional dimensions, the bending stiffness of a tower can be calculated. The vibration modes and stresses are calculated in order to perform the failure analysis. Taking a tower as a research object, Dai et al. [44] carried out a series of nonlinear time–domain analyses and collapse simulations of the failure mode of a tower under the shutdown condition. They concluded that the most plastic hinges occurred at the geometric discontinuous points of the tower. Zhang et al. [45] verified through dynamic analysis that tower buckling was the main failure mode for the wind turbine structure due to typhoon damage, mainly because the bending moment generated by the wind turbine thrust, and the gravity load of the wind turbine were superimposed to produce the combined bending load, resulting in the excessive local stress of the tower wall. To eliminate the stress concentration at the junction of the tower and flange ring, they proposed welding joints with gradient thicknesses or bolts of sufficient strength. In addition, Zhang et al. [46] proposed and verified the feasibility of adopting a load reduction system to improve the mechanical properties of the tower by studying the failure mechanism of the tower. As long as the tower did not collapse, 80% of the wind turbine components were relatively safe. Based on this, Li et al. [13] discussed the key role of the strict quality control on the tower welding joints, flanges, bolts, and other basic parts to avoid the corrosion of the parts after falling off due to heavy rain, and they finally proposed the typhoon resistance design method for the independent design of a tower.

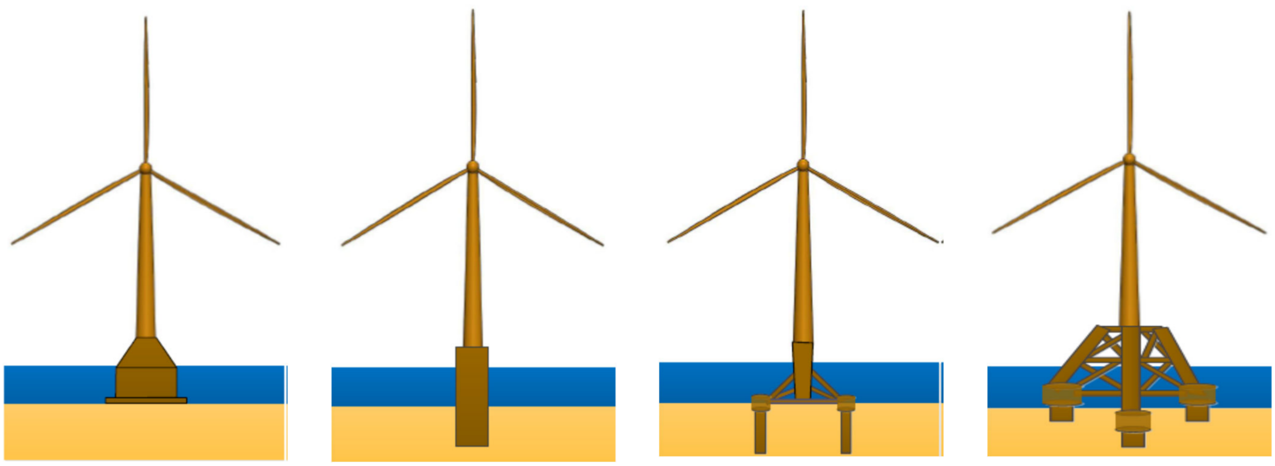
To improve the typhoon resistance of a tower, many scholars have proposed typhoon resistance design schemes based on the structure and material. Chen et al. [42] proposed distinguishing between the failure safety factors of the blade and tower in the current IEC design standard and gave priority to the strength of the tower in blade design. He et al. [47] and Liu et al. [48] concluded that reinforced concrete was suitable material for tower design because of its relatively large stiffness, large damping ratio, and good wind resistance. Chou et al. [49]. defined the risk level through risk matrix analysis. Then a variety of protective strategies against damage were proposed. Given the high risk of "tower buckling" and" bolt fracture," it was proposed to thicken the tower wall, replace the strong bolt, and increase the number of bolts to strengthen the joint. The solution provided by GE engineers for the 4 MW typhoon-proof wind turbine is to construct the tower with thicker steel, reinforcing the turbine against the stronger winds. Additionally, the turbine blades are shortened, making them more robust and helping them stand up to higher wind speeds [50].

Based on the existing literature research, for the structural design of a tower in typhoon-prone areas, wind tunnel tests or other appropriate analyses should be conducted to determine the effects of the wind direction on the wind turbines. The radius and the wall thickness of a tower should be large enough to provide sufficient bending stiffness. The strengths of the tower welding joints, flanges, and bolts are important factors for the buckling strength of a tower. However, this will inevitably lead to excess bearing capacity in the typhoon-free season. The balance of security and economy is one of the key issues that need to be considered comprehensively in tower design.

3.3. Foundation and Mooring System

3.3.1. Failure Mechanism

The foundation is the key structure supporting wind turbine operation, and foundations can be divided into fixed types and floating types. As shown in Figure 5, the fixed foundations include gravity, monopile, tripod, and jacket foundations. The floating foundations mainly include tension leg, semi-submersible, and Spar foundations (see Figure 6). Spar and semisubmersible floating technology are the most mature and widely used types of foundations. Given that the farther offshore the distance is, the stronger the wind intensity, offshore wind power has been developed further from the shore and in deeper water. However, when the water depth is greater than 60 m, the fixed foundation is no longer economically feasible in terms of the life cycle, power generation efficiency, and cost effectiveness. In contrast, floating platforms, with the advantage of the flexibility to water depths, exponentially multiply the area of the ocean where wind power can be deployed and have, thus, developed quickly around the world.

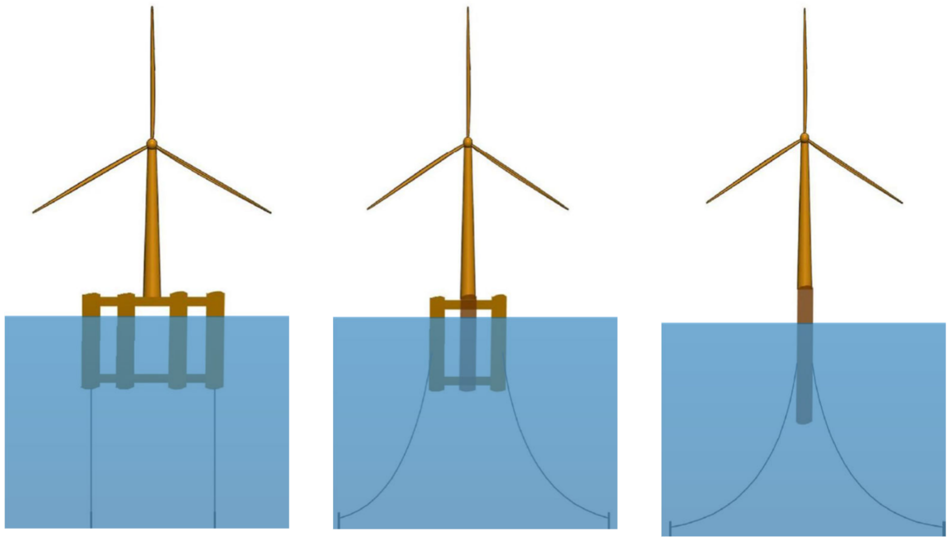


(**a**) (**b**) (**c**) (**d**)

Figure 5. Bottom-fixed offshore wind turbine foundations: (**a**) gravity; (**b**) monopile; (**c**)tripod; and (**d**) jacket.

For a fixed foundation, the huge winds and waves brought by typhoons will result in strong cyclic loads on the piles or the caissons. Large lateral deformations and even overall overturning can consequently occur [51]. Based on the plastic reliability theory, Zhu et al. [52] studied the offshore wind turbine structure reliability index change rule. It was concluded that for the condition of the typhoon foundation structure, the failure mode would develop from the single-mode damage for a variety of joint failure modes, and the structure reliability would be significantly affected by the foundation scour, the influence of the biological growth, and structure of the corrosion.

For floating foundations, in addition to the marine environmental loads, these types of foundations comply with the wave load as well as the huge thrust and overturning moment of a wind turbine. Due to the super-large structural weight and its inertia effect, once the foundation platform moves slightly, the wind turbine standing nearly 100 m away from the water causes dramatic vibration. If this coincides with a typhoon, tsunami, earthquake, or another type of natural disaster, it is very likely to cause local damage to the wind turbine (such as blade fracturing or tower yielding), or even an overall overturn. Jonkman et al. [53] compared and analyzed the influence of the floating platform movement on the bending moment and fatigue load of the blade root and tower base of three different types of floating wind turbines in the shutdown state of the ultimate sea state. Liu et al. [54] used FAST software to calculate the motion of floating wind turbines and studied the reliability of offshore wind turbine blades. The results showed that the failure probability of a blade supported by a floating foundation is greater than that of a blade supported by a fixed foundation. Tanaka et al. [55]. performed a validation of the dynamic response of a 2 MW hybrid-spar floating wind turbine during a typhoon using full-scale field data. The results showed that the consideration of the coherence of the wind was essential for the accurate estimation of the dynamic response in a typhoon environment for a spar-type wind turbine.



(**a**) (**b**) (**c**)

Figure 6. Floating wind turbine concepts: (**a**) tension leg; (**b**) semi-submersible; and (**c**) Spar.

In addition, the wave spectrum (mainly the JONSWAP spectrum) is mainly used to directly simulate the wind and waves in a floating wind turbine wave load simulation [56–58]. The wave spectrum can be used to simulate waves with basic parameters, and then the motion response and wave load of floating structures can be calculated. This indicates that the shape and development of the wave spectrum can significantly affect the prediction results [59]. Additionally, the JONSWAP spectrum is derived from the long-term observation data of the wavefield in the North Sea. Due to the differences in the water depth, water temperature, and meteorological conditions, it is not completely appropriate to use the JONSWAP spectrum directly to simulate the typhoon sea state in the South China Sea, and the principal spectrum parameters need to be modified [37,56]. Moreover, the direct parameterization of typhoon waves cannot fully reveal the dynamic mechanism. At present, parameterization is mainly used to simulate the wind-wave dominant situation, which is mostly used near the typhoon center but is not applicable to the entire typhoon wind-wave field. Under typhoon sea conditions, the characteristics of a wind wave, surge wave, and mixed wave are obvious, and the dominant part of a surge wave must be considered. The research results of many scholars around the world have verified this conclusion [60–64]. Chen et al. [65] applied the WAVEWATCH III wave model to analyze the distribution characteristics of the surge and wind waves of Typhoon "Muifa," and the characteristics of the surge and wind waves were clear. Since floating wind turbines mostly use catenary mooring positioning, they mainly have low-frequency motion. Taking the DeepCwind semi-submersible wind turbine as an example, its natural frequencies of pitch, roll, and heave are 0.06, 0.23, and 0.36 Hz, respectively [66]. Surges may cause substantial pitch motion before a typhoon approaches, and the pitch and heave motion may be stimulated when the typhoon center is close to the wind turbine. It can be seen that in the design, a JONSWAP wave spectrum is simply selected as the sea condition to analyze the limit response of the structure, and the extreme motion response may be ignored. Therefore, a floating wind turbine designed in this way may have a structural failure during a typhoon, resulting in huge economic losses. Therefore, to improve the prediction accuracy of the environmental load and dynamic response of a floating wind turbine, the influence of the wave evolution characteristics on the motion response of a floating wind turbine should be considered in the simulation of the typhoon sea wave field.

Due to the harsh ocean environment conditions, the strengths of mooring lines decrease with time, which increases the risk and positioning ability of a mooring system. After the failure of a mooring cable, the response of a floating platform and wind turbine will be different due to the mooring mode, mooring failure location, and different directions of the environmental load. Large drift motion occurs, leading to collision risk in wind farms [37]. Because of the differences in the drift motion, and wind farm layout, it is proposed in Ref. [67] that detailed simulation and tests of various failure situations are still needed.

3.3.2. Typhoon Resistance Design

The destruction of offshore wind turbines by typhoons has received increased attention. Many studies on floating wind turbines have adopted typhoons as the survival condition [4,68–70]. To improve the stability of a wind power system under typhoon sea conditions, Liu et al. optimized and designed a new model combining a multi-segment mooring line and an inclined column based on the DeepCwind floating platform by changing the connection mode of the mooring line and the structural form of a semi-submersible platform [71]. By comparing the motion of the two models, the effectiveness of the new model in reducing the pitch and heave motion of the semi-submersible platform was verified. To mitigate the dynamic responses of the support foundation under extreme winds, vibration control devices, such as tuned mass dampers (TMDs), were applied. Lian et al. [72] proposed a new eddy current with a tuned mass damper (EC-TMD) system to alleviate the structural vibrations of the offshore wind turbine supported by composite bucket foundations. Barbanti et al. [73] conducted the optimization of the mooring system of the Spar platform under harsh sea conditions. First, it was verified by numerical analysis that the additional weight block of the mooring system had an obvious optimization effect on the motion response of the Spar platform. Second, it was concluded that the mooring tension and fatigue damage could be reduced when the fairlead was near the center of mass, and then the pitching motion could be inhibited.

At present, global floating wind turbines have just entered the commercial stage, and the floating wind turbines in China are still in the prototype validation stage. There are few studies on the typhoon resistance design of a floating foundation. Future research can focus on the following aspects: (1) The application of new simple materials, such as concrete: First, this has great potential for industrialization through standardization and mass fabrication. Ultimately, not all fabrication yards can complete the steel manufacturing required by the floating foundation. Second, concrete is not sensitive to fatigue effects. Third, concrete and other high-density, low-price ballast materials can effectively lower the center of gravity, hence reducing steel consumption. (2) Given the fact that floating wind turbines are far away from the shore, the long-distance transmission of electricity should be noticed. However, the wind and rain brought by typhoons can cause damage to power transmission lines. One of the important ways to avoid the loss of power for long-distance transmission is to combine floating wind turbines with hydrogen production. This combination can reduce the cost of wind farms, improve the utilization rate of wind power, and help to determine a method for large-scale and diversified wind power development.

3.4. Control System

The control system can collect the wind speed, wind direction, and vibration signals in real time and carry out the blade pitching and yaw according to the dynamic response and vibration characteristics. This plays an important role in avoiding resonance between the wind turbine and the sea waves.

(1) Pitch control system: This system consists of pitch sensors, a computer-based or microprocessor-based controller, and a pitch actuator. This system can stabilize the wind turbine output power, increase the aerodynamic damping, and reduce the aerodynamic load of the blades.

If the wind speed of the typhoon exceeds the design limit of the wind turbine, the external pitching load may exceed the braking torque of the pitch system. At the same time, after about 10 years of long operation, the wear of the pitch actuator will result in a reduction in the braking torque. These two situations will lead to the failure of the brake of the pitch actuator, thus causing the blade to leave the feathering state so that the rotor starts to rotate until the serious consequences of rotor racing or tower collapse occur. After typhoon Rammasun landed, the field data of the Warrior wind farm showed that all the nacelles of the damaged wind turbines faced the downwind direction, and the blades were not at the feathered position. The insufficient brake torque could not keep the blades locked and the blades feathered, which led to the collapse. It could be seen that the braking of the blade rotor mechanism was particularly important for the self-existing condition of the storm. During Typhoon Saomai, the wind turbines were automatically shut down due to strong winds and turbulence, and the yaw system failed due to power grid failure. The failures of both the pitch system and the yaw system led to the blades being out of control. It is important to increase the backup power and backup safety mechanism for wind turbines to prevent a chain reaction caused by the failure of the rotor system [13,49].

(2) Yaw system: The yaw system is mainly composed of the yaw bearings, yaw gearboxes, yaw motor drivers, encoders, wind vane, and main controller. The system is designed to maximize the acquisition of wind energy. It can ensure that the rotor is facing the wind. Under typhoon conditions, the wind turbine commonly adopts the method of passive or active yaw to reduce the structural loads. Thus, the yaw drive and control system should be improved in terms of the following aspects. The first aspect is the high reliability and appropriate redundancy measures. The second aspect is the provision of enough torque to overcome the huge inertia and wind thrust of the nacelle and rotor when yawing starts. The third aspect is that the yaw drive system should be able to provide enough dynamic torque to prevent the overspeed or reverse yaw from occurring.

Ref. [74] showed that the duration of impact vibration induced by yaw was mainly determined by the yaw amplitude and its variation. The yaw control could also effectively weaken the wake effect, make the wake offset, and greatly reduce the negative effect of severely weakening the power output of wind turbines [75]. Hallowell et al. [76] established the structural failure probability model of offshore wind turbines with the action of hurricanes and quantitatively studied the influence of the yaw control system on the reliability of offshore wind turbines with the action of typhoons. The results showed that the failure probability of nine single piles with a yaw control system was $7.3 \times 10\hat{}^{-10}$~$3.4 \times 10\hat{}^{-4}$, while the failure probability of nine single piles without a yaw control system was $1.5 \times 10\hat{}^{-7}$~$1.6 \times 10\hat{}^{-3}$, with consideration of the combined action of the wind and waves caused by the hurricane. This indicated that the yaw system is an important structure for preventing the failure of the tower.

However, the frequent action of the yaw system is an important cause of wind turbine failure [77]. Therefore, to reduce the yaw mechanism movement frequency to ensure that the wind turbine has a certain adaptability, Jiao et al. [78] proposed an adaptive yaw control strategy based on a Kalman filter. The digital simulation and field test data showed that this strategy improved the accuracy for the wind and enhanced the feasibility and effectiveness of the electricity. Ben et al. [74] designed a variable structure model reference adaptive speed discriminator to effectively identify the speed of the yaw motor of a wind turbine and to optimize the anti-platform risk control strategy of the yaw system by establishing a sensorless vector control system of the yaw motor. Tao et al. [79] designed a yaw drive system and its control strategy based on a rectifier and an inverter. The technical feasibility of the scheme was verified with the yaw test platform. Li et al. [13] proposed that a hydraulic brake mechanism should be used instead of a slider brake mechanism and that a planetary gearbox should be used instead of a worm gearbox to avoid a yaw system failure in a typhoon.

The aim of the control strategy is to reduce the load amplitude under typhoon conditions and ensure the safe operation of a wind turbine. A yaw system can ensure that a wind turbine can track the change of the wind direction in real time during a typhoon. Therefore, always keeping a wind turbine in the yaw error range is the key to resisting typhoons. Ref. [80] presented an active control strategy for large wind turbines for defense before a typhoon. The control strategy embedded a series of targeted functions into the existing mainstream control logic so that the wind turbine can effectively reduce the impact of the typhoon on the unit through a series of actions, such as pre-typhoon preparatory action and yaw control strategy during the typhoon. Bao et al. [81] established a rigid–flexible multi-body model to analyze the typhoon-induced dynamic response of a wind turbine and discussed the influence of different yaw angle positions on the wind load and vibration characteristics of the structure. The results showed that when the yaw angles of the wind turbine were 30° and 120°, the typhoon-induced wind load and the wind vibration response of the structure were very significant, and the adverse yaw condition needed to be avoided in practical control. Ma et al. [82] and Garciano et al. [83] studied the failure model and overall control strategy under extreme environmental loads. By analyzing the aerodynamic characteristics of a wind turbine under a typhoon load, an active stopping strategy was proposed. The active stopping strategy proposed by the latter study had the goal of reducing the maximum aerodynamic response of a floating offshore wind turbine system during typhoon events, while the former study was based on the yaw drive system to further analyze and propose the optimal stopping position of a wind turbine. Through comparative analysis of the field data, He et al. [84] reported that the extreme difference of the wind direction deviation angle in a nacelle was the main reason for the increase in the load on a wind turbine. At the same time, considering the extreme wind speed and abrupt wind direction, the authors proposed a combined control strategy to optimize the variable pitch control and yaw control.

Based on the findings from previous work, the summary of the failure mechanism of different wind turbine components due to typhoons is listed in Table 3. The design implications to improve the typhoon resistance of the offshore wind turbine components are also suggested.

Table 3. Summary of failure mechanism and design implications of the offshore wind turbine.

Wind Turbine Component	Failure Mechanism	Design Implications
Blade	Overloading due to abnormal characteristics of typhoons	Aerodynamic shape optimization; high reliable numerical tool
Tower	Local inelastic buckling due to steel yielding	Structural strengthening
Foundation and mooring system	Fix foundation: overall overturning due to cyclic load; Floating foundation; large drift motion due to broken mooring system	Accurate coupling dynamic simulation tool considering the whole process of typhoons
Control system	Power grid failure; mechanical failure	Control strategy optimization

4. Typhoon Resistance Strategy for Wind Farm Operation and Maintenance

An offshore wind farm has a harsh environment and is subject to such factors as salt spray corrosion, large wave force, sea ice impact, and typhoon damage [21], resulting in the high failure rate of wind turbines. In addition, the short operation window period due to the influence of weather, the high cost of operation, and maintenance greatly increase the operation and maintenance cost of offshore wind farms. The operation and maintenance costs of offshore wind power are twice those of onshore wind power. The reduction in the operation and maintenance costs of offshore wind farms is the key to improving the efficiency and sustainable development of offshore wind farms. To achieve this goal, the operation and maintenance mode of offshore wind farms requires a series of upgrades for the software and hardware.

(1) Risk assessment. Risk assessment is one of the important ways to reduce damage to wind turbines caused by environmental natural disasters. To establish a reliable risk model, accurate simulations of the environmental loads, structural response, and failure probability are critical. The presence of hurricanes (tropical cyclones in the Atlantic Ocean) is a threat to the wind farms located on the Gulf and Atlantic coasts of the U.S.A. Several studies about quantifying the effect of hurricanes on the responses of offshore wind turbines have been performed. Kim and Manuel [85] developed a framework for the hurricane risk assessment of offshore wind turbines with consideration of the spatial distribution of wind and wave fields and time–domain simulations of turbulent winds and irregular waves. Rose et al. [86] proposed a probabilistic model to estimate the number of offshore wind farm turbines that would be destroyed by hurricanes and the safety risk index for four representative offshore wind farms along the Atlantic and Gulf coasts. Mardfekri and Gardoni [87] developed a probabilistic framework for the assessment of offshore wind turbines subjected to both hurricanes and earthquakes, including soil–structure interaction. Furthermore, Hallowell et al. [88]. proposed a methodology for estimating the probability of offshore wind turbine support structure failure due to hurricanes with consideration of the site-specific design of the support structure, the spatial variability in the wind and wave fields appropriate for hurricanes, the effect of changing the water depth within a wind farm, the effect of breaking waves, and structural fragility estimation based on relevant structural experiments. These risk quantification frames can be applied to the quantitative measurements of the risk to offshore wind turbines from typhoons. Li et al. [89] assessed the risk imposed by a tropical cyclone to wind farms for a selected southeast coastal region of China by employing a synthetic full track tropical cyclone simulation to generate a large dataset of statistically representative tropical cyclone events. A probabilistic framework was set up to quantify the tropical cyclone-induced risk of offshore wind farms.

(2) Periodic inspection and maintenance. Structural vibration monitoring and operational modal analysis are important ways to control the operational behavior and structural safety of offshore wind turbines. Dong et al. [90] discussed the structural response regular pattern and vibration safety under three typhoon conditions for the structural vibration displacement signals of one Chinese offshore wind power prototype. The data showed that the structural vibration was mainly affected by the rotation speed rather than the wind speed. A wind turbine should be monitored for key items before the typhoon season. The bolt torques of components, such as the pitch brake, shaft, and generator, should meet the requirements. The UPS batteries should be in good condition to ensure the reliability of the pitch system. The hydraulic system and the transmission mechanism in the control system should be functional to lock the blades. The loops of the overspeed protection and vibration protection should connect normally to survive in typhoon conditions. The deep integration of artificial intelligence and wind power technology enables the wind turbine to have the characteristics of high reliability and high efficiency. Envision Energy developed a "super perception" intelligent offshore wind turbine. A wind turbine with intelligent fault diagnosis

ability can solve a fault in real-time operation, thus eliminating the risk that may lead to failure.

(3) Disaster warning. A disaster warning is an important part of reducing the destruction of a typhoon. According to the typhoon disaster warning information issued by the meteorological administration, a wind farm should track the movement of the typhoon path and the wind and rain intensity in real time. Relying on cloud computing, big data, and artificial intelligence, the meteorological, ocean, ship, and wind farm information can be intelligently analyzed. Yang et al. [91] reported that current offshore wind farms lacked effective real-time sea state detection and accurate meteorological forecasting systems. Thus, it is necessary to build an intelligent scheduling system of maintenance ships for offshore wind farms. The intelligent management system for offshore wind power should integrate a visual display, customized fine forecasting, real-time maritime warning, and ship/personnel-integrated management.

5. Conclusions

Typhoon damage is a key factor in the design and operation of offshore wind turbines, and it is directly related to the stability and safety of wind turbines and the economy of wind farms. This paper provides an overview of the recent developments of typhoon resistance design and strategy for offshore wind turbines and puts forward the following conclusions and prospects:

(1) The passage of a typhoon is accompanied by extreme wind and wave loads. At present, there are adequately measured data for typhoon wind fields, and the numerical simulation method is mature. However, there are few published measured data for high-quality continuous observation data for typhoon waves, so numerical simulation research should be carried out. In addition, the influence of the wave evolution characteristics on the wind turbine motion response during the passage of a typhoon should be considered.

(2) Through the optimization of structure and material, the typhoon resistance of an offshore wind turbine blade and tower can be enhanced. Further research into the numerical aerodynamic tools for the nonlinear response of a wind turbine subjected to typhoons incorporating mesoscale and microscale numerical models is necessary to achieve reliable structural analysis. The calculation accuracy of the ultimate load and failure mode should be improved to balance the safety and economy of an offshore wind turbine.

(3) According to the characteristics of the high wind speed and varying wind direction of a typhoon, the combined control strategy of the pitch, yawing, and braking of a typhoon is of major concern for effectively improving the survival ability of wind turbines under typhoon conditions.

(4) The wind farm in southeastern China needs to establish an intelligent operation and maintenance mode, integrating warning and management for a typhoon in order to achieve the goal of reducing the cost and increasing the efficiency of offshore wind farms.

At present, the research on the typhoon resistance of offshore wind turbines is mainly based on experience with onshore wind turbines and offshore fixed wind turbines, and there are few practical studies on the survivability of floating wind turbines under typhoon conditions. A floating wind turbine positioned by a mooring system has more complex structural and motion characteristics. The high wind speed and large waves in the typhoon sea state significantly challenge the survivability of the mooring cables. Typhoons are the control loading for floating wind turbine design in China. Due to the limited guidance at present, it is necessary to carry out further research on the typhoon resistance design of a mooring system. Additionally, the evolution of coupling motion characteristics and the structural loads during the whole process of typhoons is worth being investigated.

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