Structural integrity of wind turbines impacted by tropical cyclones: A case study from China

Xiao Chen*, Chuanfeng Li, Jing Tang
National Laboratory of Wind Turbine Blade Research & Development Center, Institute of Engineering Thermophysics, Chinese Academy of Sciences, 11 Beisihuanxi Road, Beijing 100190, China
*drchenxiao@163.com

Abstract. This study presents a case study on wind turbines impacted by tropical cyclones in China. A quantitative investigation is conducted by integrating aerodynamic, aero-elastic and structural analysis to provide insights into structural integrity of wind turbines under extreme wind conditions. Local mean wind profiles at each turbine site are reconstructed using three-dimensional CFD calculation considering terrain topography of the wind farm. Failure modes and failure locations of rotor blades and tubular towers are predicted using finite element analysis. “The lesser of two evils” principle in the turbine design is addressed regarding the criticality of blade fracture and tower collapse. Referring to the current IEC standard for wind turbine design, it is suggested that the partial safety factor associated with failure of turbine tower should be larger than, instead of equal to, the one for the rotor blade to reduce the risk of the total loss of wind turbines in extreme wind conditions.

1. Introduction
Tropical cyclones such as typhoons and hurricanes severely endanger structural integrity of wind turbines (WT) installed in the coastal regions. When a wind farm is impacted by a typhoon, typical structural failures like blade damage, tower collapse and turbine foundation overturning occur as shown in Table 1. Some basic wind information of these typhoons is listed in Table 2. This study focuses on structural failures caused by Dujuan and Usagi.

| Time    | Typhoon | Wind farm (Shortest distance to TC*) | Total WT number | WT rated power (kW) | Blade damage | Tower collapse | Foundation overturning |
|---------|---------|-------------------------------------|-----------------|----------------------|-------------|----------------|------------------------|
| 2003.09 | Dujuan  | Guangdong Hongzhawan (40~50km)      | 25              | 660                  | 9           | 0              | 0                      |
| 2006.08 | Saomai  | Zhejiang Cangnanshan (30~40km)      | 28              | 250(x3), 550(x2), 600(x19), 660(x2), 750(x2) | 15          | 3              | 2                      |
| 2010.10 | Megi    | Fujian Linao (10~15km)              | 85              | 850(x36), 1250(x36), 2000(x13) | 1           | 1              | 0                      |
| 2013.09 | Usagi   | Guangdong Hongzhawan (10~15km)      | 25              | 660                  | 11          | 8              | 0                      |
| 2014.07 | Rammasun| Hainan Wenchang (60~70km)           | 33              | 1500                 | 2           | 1              | 0                      |
|         |         | Guangdong Xuanwu Warriors (20~30km)|                 |                      |             |                |                        |

*The shortest distance between the location of the wind farm and the center of the typhoon (TC). The distances are measured by Google Earth based on typhoon best track data which are downloaded from the Joint Typhoon Warning Center (JTWC) [1].
Table 2 Basic wind information of typhoons those impacted Chinese wind farms

| Typhoon | Maximum wind speed (m/s) | Wind intensity classification |
|---------|--------------------------|-----------------------------|
|         | Along the entire typhoon track | At the landfall location | By Saffir-Simpson scale [2] | By Chinese typhoon scale [3] |
|         | 10-minute sustained | 1-minute sustained | 2-minute mean | |
| Dujuan  | 41.7                  | 63.9                  | 33           | Category 4 Typhoon |
| Saomai  | 54.2                  | 72.2                  | 60           | Category 5 Super Typhoon |
| Megi    | 63.9                  | 81.9                  | 38           | Category 5 Typhoon |
| Usagi   | 56.9                  | 69.4                  | 45           | Category 4 Strong Typhoon |
| Rammassun | 45.8                 | 72.2                  | 48           | Category 5 Strong Typhoon |

Only a few studies [4,5] have been performed to investigate structural failures of wind turbines under such extreme wind conditions due to the complexity of this issue. The development of offshore wind energy is expected to speed up in China in the years to come according to the recent government planning [6], and there is an urgent need for studies to gain in-depth understanding of structural integrity of wind turbines under extreme wind conditions and to bridge the gap between wind energy industry and academia. Because tremendous complexity is involved in modelling the combined event of typhoon winds, turbine operational status, wind farm conditions, wind turbine characteristics, etc., some assumptions are necessary and have to be introduced in this study. The analysis is performed as quantitatively as possible provided with available data. Qualitative analysis is also presented based on post-mortem observation and inquiries of wind farm operators. A comprehensive framework is established to guide the process of this study by integrating aerodynamics, aero-elasticity, operation and structural analysis. Major parts of this study include:

(1) Presenting structural failure characteristics of a coastal wind farm catastrophically damaged by two typhoons, i.e., Dujuan and Usagi. Background information on typhoons, wind farm and wind turbines has been collected and analyzed; post-failure investigation has been conducted to identify failure modes and characteristics of wind turbines from a phenomenological perspective.

(2) Constructing a multidisciplinary framework to quantitatively investigate failure response under typhoon impact with necessary and appropriate assumptions. In the framework, typhoon wind profiles are extrapolated based on available meteorological measurements. To consider the terrain effect on wind speeds, local mean wind speeds at each turbine site are calculated using three-dimensional (3D) Computational Fluid Dynamics (CFD) method considering terrain geographic features reconstructed from Global Positioning System (GPS) data; aero-elastic analysis is subsequently performed using the FAST code [7] assuming that wind turbines are in an emergency state with different rotor stop positions; detailed structural analysis is finally performed based on Finite Element (FE) models to reproduce failure response of the rotor blades and tubular towers.

(3) Proposing suggestions to modify the current IEC standard [8] for wind turbine design. The clauses which specify the partial safety factors for consequence of failures during ultimate strength analysis of wind turbines are examined and discussed. Suggestions for modification are made accordingly.

2. Background

In order to investigate structural failures of wind turbines, it is foremost to know the wind conditions at the location where the wind farm locates. Preferably, the wind speeds at each individual wind turbine site have to be found out taking into account of the terrain effect. There are several measurements of wind speeds near or at the wind farm as shown in Table 3, in which $V_{10\text{min}}$, $V_{2\text{min}}$ and $V_{3s}$ are the maximum wind speeds averaged over a 10-minute, 2-minute and 3-second period, respectively. Anemometers installed on the wind turbines provide important information on local mean wind speeds at each turbine site but they are only available for the case of Dujuan. Estimation has to be made to obtain the local mean wind speeds at each turbine site for the case of Usagi, which is the motivation of the CFD calculation of this study.

The wind farm is located on a small island at the coast of Shanwei city, see Figs. 1(a) and (b). Most blade damage occurred on wind turbines located on the west ridge while most tower collapse occurred on wind turbines located on the flat terrain in the middle of the island as shown in Figs. 1(c) and (d).
The direct loss of the wind farm due to damage of components was estimated to be $1.6 million and $16 million for Dujuan and Usagi, respectively.

Table 3 Wind speeds recorded near or at the wind farm during the typhoon passage

| Typhoon | A weather station near the wind farm @ 10m above the ground level | Anemometers installed @ hub height of 25 wind turbines |
|---------|---------------------------------------------------------------|---------------------------------------------------|
| Dujuan  | \( V_{2\text{mean}, 10m} = 21\text{--}29 \text{ m/s, NE} \) | \( V_{10\text{min}, \text{hub}} = 30\text{--}41 \text{ m/s at different turbine sites} \) |
|         | \( V_{10\text{m}, 10m} = 33 \text{ m/s, NE} \) | \( V_{3\text{s}, \text{hub}} = 40\text{--}57 \text{ m/s at different turbine sites} \) |
| Usagi   | \( V_{2\text{mean}, 10m} = 40 \text{ m/s, SSW} \) | Measurement data are not available. Wind speeds to be estimated using CFD calculation |
|         | \( V_{10\text{m}, 10m} = 45 \text{ m/s, NNE} \) | |
|         | \( V_{3\text{s}, 10m} = 40\text{--}57 \text{ m/s} \) | |

Fig. 1 The wind farm under study (a): Two typhoon tracks, (b): The location of the wind farm, (c): Damage distribution due to Dujuan, (d): Damage distribution due to Usagi

It should be noted that despite the specified survival wind speeds of 70 m/s for 3 seconds and 50 m/s for 10 minutes as shown in Table 4, the wind turbines were severely damaged by the winds with much lower wind speeds. The maximum wind speeds recorded at the hub height were only 57 m/s for 3 seconds and 41 m/s for 10 minutes under the impact of Dujuan. This suggests that the wind turbines did not have adequate strength against the extreme winds.

Table 4 Technical specifications of the wind turbine under investigation

| Item              | Value                   |
|-------------------|-------------------------|
| Wind turbine class| IEC Class I             |
| Rotor diameter    | 47 m                    |
| Blade length      | 22.9 m                  |
| Hub height        | 45.7 m                  |
| Survival wind speed at hub height | 50 m/s for 10 minutes |
|                   | 70 m/s for 3 seconds    |

Post-failure observation found that Usagi caused severer damage to the blades than Dujuan did. Only the outside shells of the blades were found to be fractured due to Dujuan impact as shown in Fig. 2(a), while the complete breakage and thus the total loss of the load-carrying capacity of the blades occurred due to Usagi impact, see Fig. 2(b). Nevertheless, the failure location ranged from 6 to 14 m in the span-wise direction of the blades. For the 8 tubular steel towers subjected to collapse due to Usagi impact, the same failure mode of local buckling was observed at a tower height from 9 to 10 m. Also of interest is that all towers collapsed towards a same direction of SSW or SW, suggesting a prevailing wind force acting on the turbines from NNE or NE.

3. Proposed framework of study

Conducting a quantitative study on this failure case requires multidisciplinary knowledge from aerodynamics, aero-elasticity, structures, materials, controlling, etc., and it is necessary to develop a systematic approach to guide the failure investigation process. In addition, some assumptions have to be introduced to simplify the analysis. They include:
The flow field of the investigated wind farm is regarded to be quasi-steady during two typhoon events. This assumption is appropriate for this particular case because, on one hand, the size of the island on which the wind farm locates is approximately 5.80 km x 5.58 km, which is much smaller than the spatial scale of typhoons which have a radius ranging from 500 to 1000 km, see the scale bars indicated in Fig. 1. The change of wind direction and wind speed at the concerned site lasts a relative long period of time, i.e., several hours, in a progressive manner. On the other hand, the island is geographically flat with the peak elevation of 56 m and a maximum inclination of approximate 6.5°. No obvious vortex shedding was found in the wake of the ridges on the island during the preliminary computations. In this regard, the steady Reynolds averaged Navier-Stokes (RANS) method is used in this study to calculate local mean wind speeds at each turbine site in the wind farm.

Structural failure of wind turbines is controlled by ultimate strength. Considering that high wind speeds are most likely responsible for the observed structural failure, the maximum wind speeds are used to calculate extreme wind loads and verify the ultimate strength of the wind turbines, which are expected to sustain the extreme winds with speeds of 70 m/s for 3 seconds and 50 m/s for 10 minutes according to the turbine specification. This study uses 3s-mean wind speeds to calculate the extreme wind loads applied to the wind turbines.

Wind turbines are stationary due to an emergency stop state. The assumption is reasonable because the wind farm is reported to experience power loss during typhoon passage, leading to an emergency stop state of the wind turbines. In this state, both the yaw and the pitch system are locked, and mechanical disc brakes are applied. Given this condition, the aero-elastic analysis is performed on the wind turbines with representative stop positions in this study.

Composite blades and tubular steel towers have no manufacturing defects. The FE models of structures are reconstructed according to the information from design documents, field measurements and inquires of wind farm operators and turbine owners.

Given the aforementioned assumptions, the framework of this study as schematically shown in Fig. 3, is constructed as follows: The wind farm terrain is numerically reconstructed using GPS data. The 3D geographical model of the terrain is then used in CFD calculations to obtain the wind profiles along the turbine height at each turbine site, considering the terrain effect on local mean wind speeds. The wind inputs to the CFD calculations are based on the recorded wind data at a specific height and extrapolation using the existing wind profile model particularly for typhoons [9]. Wind loads acting on the wind turbines are then calculated considering rotor positions in an emergency stop state. Composite blades and tubular steel tower are reconstructed in FE models. Consequently, nonlinear structural analysis is conducted to reproduce structural failures of wind turbines along with discussion on the current design method.
4. Numerical modelling

4.1 CFD simulation of local winds in the wind farm

(1) Simulation method

The atmospheric flow of the wind farm is predicted by solving the incompressible RANS equations using the commercial FLUENT code [10]. The equations are discretized using finite volume method and the second order upwind algorithm is used for the spatial discretization. Pressure-velocity coupling is carried out using SIMPLE algorithm. The turbulence is modelled by the two equations standard \( k-\varepsilon \) model with model constants modified according to reference [10].

A user-defined wall function for the near-wall treatment is used assuming that the atmospheric boundary layer friction velocity \( u^* \) is equal to the laminar bottom layer friction velocity \( u_{\tau_0} \). For a fully turbulent region [12]:

\[
u^* = \frac{1}{\kappa} \ln \left( \frac{z_p}{z_0} \right) = \frac{1}{\kappa} \ln \left( \frac{z^*}{Z^*_0} \right) \tag{1}
\]

where \( u^* \) is the dimensionless wall tangential velocity. The dimensionless height \( z^* \) is defined as \( z^* = \frac{z_p v}{\nu} \), where \( \nu \) is the kinetic viscosity of the flow, and \( z_p \) is the distance from the center of the first grid cell to the wall surface, \( z_0 \) is the roughness length of the wall, \( Z^*_0 = \frac{z_p \mu_{\tau_0}}{\nu} \) is the dimensionless roughness length, and \( \kappa \) is the von-Karman constant which is 0.41 in this study.

(2) Grid

The 3D grid of the computational domain with a size of 5790m×5580m×500m (x×y×z) is shown in Fig. 4. The height of the domain is considerably larger than the peak elevation of the terrain so that the influence of the terrain on the top surface of the domain could be ignored. Structured grid method is used to mesh the domain and the total number of grid cells are 500×500×55. The bottom surface of the domain characterizing the terrain are meshed with equidistant spacing grids in x and y directions. The height of the first grid is determined based on the roughness length \( z_0 \), and the height of grid cells along z direction was changed incrementally from \( 2z_p \) to 3.0 m in the region between terrain surface and the top height of wind turbines.
(3) Boundary conditions
According to reference [13], the roughness length $z_0$ ranges between 0.03 and 0.1m for an open terrain such as nearshore water with a wind speed larger than 30m/s and countryside with low grasses. The value of 0.1m was used for the island ground based on its vegetation condition and the upper bound value of 0.1m was used for nearshore water considering that the recorded wind speed is much higher than 30m/s during the typhoon event.

The bottom surface, or terrain surface, of the domain is defined as a non-slipped wall, and the top surface of the domain is defined as a symmetry boundary assuming that the atmospheric flow is fully developed at the altitude. For the four vertical sides of the domain, velocity inlet or outflow boundary conditions are applied based on different wind directions.

For a neutral atmosphere, the wind speed $u_z$ increases logarithmically with height $z$ and it can be described by equation (2). Neutral or near-neutral atmosphere conditions have been observed to prevail at high wind speeds [14], and Powell et al. [9] proved that logarithmic model of Eq. (2) was able to well describe wind profiles of tropical cyclones. Therefore, Eq. (2) was adopted to model the wind speed distribution of the velocity inlet boundary.

$$u_z = \frac{u^*}{\kappa} \ln \left( \frac{z}{z_0} \right)$$  \hspace{1cm} (2)

where $u^*$ is the atmospheric boundary layer friction velocity which could be estimated using the recorded wind speed at 10m elevation, i.e., $u_{10}$.

For the velocity inlet boundary the longitudinal log-law velocity distribution is used and decreased shear stress is introduced to modify the turbulent kinetic energy [12]. The turbulent kinetic energy, $k$, and turbulent dissipation rate, $\varepsilon$, are defined as follows:

$$k = \frac{u'^2}{\sqrt{C_\mu}} \left( 1 - \frac{z}{h_g} \right)^2$$  \hspace{1cm} (3)

$$\varepsilon = \frac{u'^3}{\kappa z^2}$$  \hspace{1cm} (4)

where $C_\mu$ is a modified constant in $k-\varepsilon$ model which is 0.03 in this study, $h_g$ is Geostrophic plane elevation and it is defined as:

$$h_g = \frac{u^*}{6f}$$  \hspace{1cm} (5)

$f$ is the Coriolis parameter and is defined as $f = 2 \Omega \sin \lambda$, where $\Omega$ is angular velocity of the earth’s rotation equal to $7.2722 \times 10^{-5}$ rad/s, $\lambda$ is the latitude of the island and equals to 22.44ºN in this study.

(4) Model assessment
In order to demonstrate the capability of the model in obtaining a sustainable wind profile with the model settings, the simulation method has been applied to an empty fetch with a same size as the wind farm before actual simulation was carried out. A representative set of three wind profiles with $u_{10}$
equal to respectively 33, 47, and 57 m/s were applied to the domain inlet. The wind profiles at the middle and the center of the domain and the outlet were calculated. It is found that wind speed profiles were maintained well along the empty fetch however with minor differences within 4%. Therefore, the proposed method and the model settings are regarded to be justified and they are used to analyze the wind farm terrain.

4.2 Aero-elastic modelling for wind turbine loads

Wind turbines are expected to be completely stationary due to the emergency stop state under typhoon impact. Therefore, the wind loads acting on the turbine are determined by local winds calculated by CFD and stop positions of the turbine regarding its yaw angle, blade pitch angle and the azimuth angle. A representative set of two typical stop positions during typhoon Usagi are investigated in this study. The first one is the most likely stop position of wind turbine upon power loss when the nacelle heads towards NW and all blades are feathered as required when the pitch system works properly. Another position is also examined representing the case when one blade had pitch malfunction as observed in the field. For both cases, the azimuth angle was considered to be zero as this would result in one blade pointing upwards and sustaining a maximum wind speed. The wind coming from NNE is considered to be responsible for the tower collapse towards SSW. Turbine stop positions and wind conditions used for aero-elastic analysis is listed in Table 5.

| Nacelle direction | Blade pitch position | Wind speeds when the wind comes from NNE |
|-------------------|----------------------|----------------------------------------|
| NW                | All blade feathered as required | $V_{h, hub}=62.2$ m/s (CFD calculated) |
|                   | The top blade not feathered due to pitch malfunction | $V_{h, hub}=68.5$ m/s (CFD calculated) |
|                   | $V_{h, let}=59.9$ m/s (extrapolated) | $V_{h, hub}=68.5$ m/s (CFD calculated) |
|                   | $V_{h, inlet}=45.0$ m/s (measured) | $V_{h, hub}=62.2$ m/s (CFD calculated) |

The FAST code [7] can calculate wind loads applied to rotor blades but it does not provide function to calculate wind loads applied to nacelle and tubular tower. To overcome these limitations, the method well-established in structural wind engineering is used following the procedure specified in the design standard [15]. Resultant point loads applied to the nacelle and the tubular tower are calculated accordingly.

4.3 FE modelling of composite blade and tubular tower

Detailed structural models of tubular steel towers and composite rotor blades are represented as FE models in ABAQUS [16] based on the information obtained from turbine specification, design documents, user inquiry and field investigation. The entire wind turbine is modelled with four parts, i.e., rotor blades, rotor hub, nacelle and tubular tower. Rotor hub and nacelle are modelled as rigid parts to transfer loads from rotor to tower, see Fig. 5. Shell elements are used to mesh blades and towers. Blade roots and tower root are cantilever fixed. In order to accurately capture significant contact nonlinearity of the wrapped shells in the fractured regions, self contact is imposed to the outside surface of the tower shells in the height ranging from 7.3 to 16.8 m.

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It is noted that the wind loads calculated from aero-elastic analysis are the resultant cross-sectional point loads associated with the beam model implicitly used. Distributed wind loads are assumed and applied to structural shells in order to approximate actual wind pressures acting on the tower and the blades, see Fig. 6. For the tubular tower, the distribution of the wind loads is assumed to follow reference [17]. The tower cross section is divided into four regions. Pressure and suction loads are applied to different regions in such a way that the resultant loads pass the center of the cross section and are equal to the ones calculated from aero-elastic analysis. For the blades, the wind loads are assumed to be uniformly distributed over the spar caps, which are primarily responsible for the load-carrying capacity of the blades. The resultants of these distributed loads are equal to the lift force and the drag force of the blade cross section, which are calculated by the FAST code.

An elastic-plastic material model with isotropic hardening is assigned to the steel in the potential failure region of the tower, i.e., the same region as the one with surface self contact. An elastic material model is used in the rest regions of the tower. Composite material model is used for the blades. Large deformation is activated in the analysis enabling the prediction of the geometric nonlinearity of the models. Material properties of steels are provided by the tower manufacturer and they are shown in Table 6. Material properties of UD composites are provided by the turbine owner and those of triaxial and biaxial composites are assumed in this study based on the information from field investigation and user inquires as shown in Table 7.

| Material model | Young's modulus (E (GPa)) | Poisson's ratio (ν (-)) | Yielding strength (σy (MPa)) |
|----------------|---------------------------|------------------------|-----------------------------|
| Elastic        | 210                       | 0.28                   | -                           |
| Elastic-plastic| 210                       | 0.28                   | 345                         |

| Material | Longitudinal modulus E1 (GPa) | Transverse modulus E2 (GPa) | Poisson's ratio ν (-) | Shear modulus G12(GPa) | Longitudinal tensile εt (%) | Longitudinal compressive εc (%) | Transverse tensile εt (%) | Transverse compressive εc (%) |
|----------|-------------------------------|-----------------------------|----------------------|------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| UD       | 40.0                          | 12.0                        | 0.25                 | 3.4                    | 2.18                        | 1.28                        | 0.29                        | 1.31                        |
| Triaxial | 25.9                          | 12.1                        | 0.36                 | 7.7                    | 2.36                        | 1.83                        | 1.65                        | 1.07                        |
| Biaxial  | 12.5                          | 12.5                        | 0.40                 | 10.3                   | 1.28                        | 1.28                        | 1.28                        | 1.28                        |

5. Results and discussion

5.1 Summary of predicted structural failure

Structural failure of each case is predicted by FE analysis and the results are summarized in Table 8. Wind turbines located in the flat middle region of the wind farm are subjected to relative low wind speed equal to \(V_{hub} = 62.2\) m/s. When all blade are feathered as required, the top blade is found to be able to survive the extreme wind as it has a design survival speed of 70 m/s. All wind loads applied to
On the other hand, for wind turbines located in the west ridges, the wind speed of $V_{hub}=68.2$ m/s is very close to the design survival speed of the blade, leading to the fracture of the top blade. Upon blade fracture, the wind loads applied to the rotor are substantially reduced due to the loss of blade section. As a result, the tower survives the strong wind.

It is of interest to note that these predictions are in good agreement with the distribution of structural failure observed in the wind farm that most tower collapse is found in the flat middle region with lower wind speed while most blade fracture is found in the west ridges with higher wind speed.

Considering the cases when the top blade is not feathered due to pitch malfunction, one can find that no structural failure would occur regardless of the turbine location. This is because the top blade with pitch malfunction is happened to sustain insignificant wind loads at this particular stop position and the tower loads are consequently reduced.

Table 8 Summary of predicted structural failure

| Case | Blade pitch position | Turbine location and local winds | Top blade | Tower |
|------|----------------------|----------------------------------|----------|-------|
| #1   | All blade feathered as required | Flat middle, $V_{3s, hub}=62.2$ m/s, NNE | Survive  | Collapse |
| #2   | The top blade not featured due to pitch malfunction | West ridge, $V_{3s, hub}=68.5$ m/s, NNE | Fracture | Survive |
| #3   | The top blade not featured due to pitch malfunction | West ridge, $V_{3s, hub}=68.5$ m/s, NNE | Survive  | Survive |

The blade could survive wind loads but would be damaged as a final consequence of tower collapse.

5.2 Failure mode and failure location

Failure characteristics of wind turbines are examined taking advantage of the FE analysis. It is found that tower collapse is initiated by steel yielding and subsequent local buckling of tower shells in the thickness transition region, see Fig. 7. The location of failure is predicted to be around 10 m, which is in good agreement with the field observation. For the composite blade, it fails due to local buckling and the subsequent section fracture as shown in Fig. 8. The region of local buckling ranges from 6.9 to 10.2 m and the region of the fracture section is predicted to be 7.3 m, which also agrees well with the failure location of the blade observed in the post-failure scene.

Fig. 7 Collapse of the tower when all blades are feathered as required, $V_{3s, hub}=62.2$ m/s (Case #1)
strength should be given priority over the blade strength and the partial safety factor for severer failure to the entire wind turbine contrary to the blade fracture. It is suggested that the tower blade fracture and tower collapse as being of equal importance. However, the tower collapse causes failure in order to protect the turbine tower from collapse. The partial safety factor criticality of blade fracture and tower collapse, it is suggested that rotor blades should be allowed to fail in order to protect the turbine tower from collapse. In the current IEC design standard, the tubular tower and the rotor blade are equally treated as “non fail-safe” structural components (component class 2) with a same partial safety factor $\gamma_n = 1.0$ for consequence of failure during ultimate strength analysis. This specification essentially regards the consequences of blade fracture and tower collapse as being of equal importance. However, the tower collapse causes severer failure to the entire wind turbine contrary to the blade fracture. It is suggested that the tower strength should be given priority over the blade strength and the partial safety factor $\gamma_n$ for consequence of failure should be larger than, instead of equal to, the one of the rotor blade in the current IEC design standard.

6. Conclusion

This study found that the wind turbines, which are specified to be able to sustain a survival wind speed of 70 m/s for 3s at hub height, did not have sufficient strength under the impact of two typhoons. The maximum 3s mean wind speed at hub height was recorded to be 57 m/s in typhoon Dujuan and was calculated to be 68.5 m/s in typhoon Usagi at the location of the wind farm. Dujuan caused the fracture of the outside shells of the blades while Usagi caused the fracture of the load-carrying members of the blades and the collapse of turbine towers. For the damage due to Usagi, it was found that when all blades were feathered as required, the extreme winds, which came from NNE with a hub-height wind speed of 62.2 m/s, caused the tower collapse in the flat middle region of the wind farm. On the other hand, the extreme winds, which had a hub-height wind speed of 68.5 m/s caused fractures of rotor blades on the wind turbines located in the west ridges of the wind farm. Tower collapse was predicted to be triggered by steel yielding and the subsequent local buckling of tower shells. Blade fracture was found to be caused by local buckling and the subsequent section fracture. Considering the degree of criticality of blade fracture and tower collapse, it is suggested that rotor blades should be allowed to fail in order to protect the turbine tower from collapse. The partial safety factor $\gamma_n$ for consequence of failure should be revised in the current IEC design standard.

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