Engineering Failure Analysis 60 (2016) 391–404

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Structural failure analysis of wind turbines impacted by super typhoon Usagi

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ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form 28 October 2015
Accepted 16 November 2015
Available online 17 November 2015

Keywords:
Structural integrity
Extreme wind
Post mortem
Failure scenario
Partial safety factor

ABSTRACT

Extreme winds severely endanger structural integrity of wind turbines. In order to understand failure mechanisms of wind turbine structures under extreme wind conditions, this paper presented a study on structural failure of wind turbines damaged by super typhoon Usagi in 2013. A particular focus was placed on the effect of strong wind speed and large change of wind direction on tower collapse and blade fracture. Post-mortem investigation was conducted at field, and data of local winds, tubular steel tower and composite rotor blade were collected and analyzed. A systematic procedure was developed by integrating wind load calculation and structural modeling. Quantitative investigation on structural response of turbine towers and rotor blades was conducted to identify the root causes of failure. Failure scenarios were studied considering typical stop positions of the wind turbine. The fuse function of the rotor blade whose fracture is able to protect the tower from collapse was also addressed. Based on the findings obtained from this study, some suggestions were proposed to modify the current IEC design standard and a few potential future directions of study were addressed to reduce the risk of wind turbine failure under extreme wind conditions such as typhoon and hurricane.

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1. Introduction

More wind turbines have been installed in coastal regions where large energy demand is geographically accordant with abundant wind resource. As a result, extreme wind conditions such as typhoon and hurricane become a major threat to structural integrity of wind turbines. In recent years, structural failure accidents of wind turbines caused by extreme winds have been constantly reported based on qualitative observation and phenomenological assessment [1]. Only a few studies have been carried out in a quantitative manner to analyze wind turbine failure. Among them, T. Ishihara et al. [2] investigated the collapse of two turbine towers caused by typhoon Maemi in Japan in 2003 and found that the maximum bending moment of the collapsed towers was larger than their ultimate bending moment during typhoon impact. J.S. Chou et al. [3,4] examined the likely causes of tower collapse and rotor blade damage of a wind turbine during typhoon Jangmi in Taiwan in 2008 and found that insufficient strength and poor quality control of bolts were the causes of the tower collapse during strong winds, and insufficient blade material strength, wind frequency and resonance effect and human error during turbine installation were identified as main causes of blade damage.

As the world's largest regional market of wind energy in terms of both the cumulative capacity and the newly installed capacity [5], China suffers severely from typhoons as an average of nine typhoons make landfall on its southeastern coasts annually according to F.J. Xiao et al. [6]. Although structural failure of wind turbine was reported frequently after typhoon impact, very little study is conducted to investigate failure accidents that occurred in China. There is an urgent need of study on wind

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http://dx.doi.org/10.1016/j.engfailanal.2015.11.028
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turbine failure in order to provide valuable understanding on not only how and why wind turbines response under extreme wind conditions but also what possible measures one could take in the design practice to reduce the risk of structural failure of wind turbines.

The current study, with an aim to partly fill the gap between academic research and the fast-growing offshore wind energy industry, conducts an investigation on a coastal wind farm which was catastrophically damaged by super typhoon Usagi in 2013. During this endeavor, structural failure of wind turbines was carried out from a post mortem perspective. The post mortem analysis (PMA) is commonly used in the software engineering to determine and analyze elements of a completed project that were successful or unsuccessful [7]. The purposes of conducting PMA include identifying root causes of problems and successes that happened in the project, informing process improvements which mitigate risks of future projects, and incorporating lessons learned from a single project into organization lessons learned, etc. [8,9]. In recent years, the PMA method is also adopted by material, mechanical and energy engineering to analyze the failure of materials and mechanical components under certain service conditions [10–13].

The current study uses the PMA approach to investigate the wind turbine failure. It is of interest to identify root causes of structural failure and propose possible measures to reduce the risk of similar failure, especially when the current design practice is of concern. Tremendous efforts were made to collect, analyze and interpret data of typhoon winds, wind turbines and the wind farm. A systematic procedure was developed to examine structural response of wind turbine in a quantitative and iterative manner by integrating both wind characterization and structural analysis. A particular focus was placed on the effect of strong wind speed and large change of wind direction on structural failure when wind turbines stop at an emergency state due to power loss. An attempt was made to correlate structural failure behavior of wind turbines to the current design standard for possible modification. It is expected that some insights gained from this study could assist structural failure mitigation of wind turbines in typhoon/hurricane-prone coastal regions not only in China but also worldwide.

2. Super typhoon Usagi

On September 16, 2013, Usagi developed into a tropical storm east of the Philippines. It began explosive intensification on September 19 and ultimately became a violent and large typhoon [14]. Based on satellite estimates of intensity by The National Aeronautics and Space Administration (NASA), within 24 h Usagi intensified by 33.3 m/s and reached a peak wind of 69.4 m/s [15]. According to the Saffir–Simpson hurricane intensity scale [16], Usagi reached the upper bound of the Category 4 which specifies a sustained wind speed from 58.1 to 69.7 m/s, and it was classified as a super typhoon according to China Meteorological Administration [17]. Usagi made landfall on September 22 in China's Shanwei city where a coastal wind farm located. The Usagi track is shown in Fig. 1.

During Usagi impact, the maximum wind speed of 3 s average and the corresponding wind direction at 10 m elevation were recorded at a local meteorological station near the wind farm, see Fig. 2. It can be seen that the wind first blew from NW at a maximum speed of 33 m/s and continued to increase speed and change direction clockwise. The peak wind speed reached 57 m/s when the wind blew from SSW and the wind direction changed nearly 250 degree, which is within the range of ± 180 degree specified in the international standard of wind turbine design [18]. The strong wind speed and the large wind direction change characterize Usagi and they are placed with major focus during structural failure analysis of wind turbines in this study.

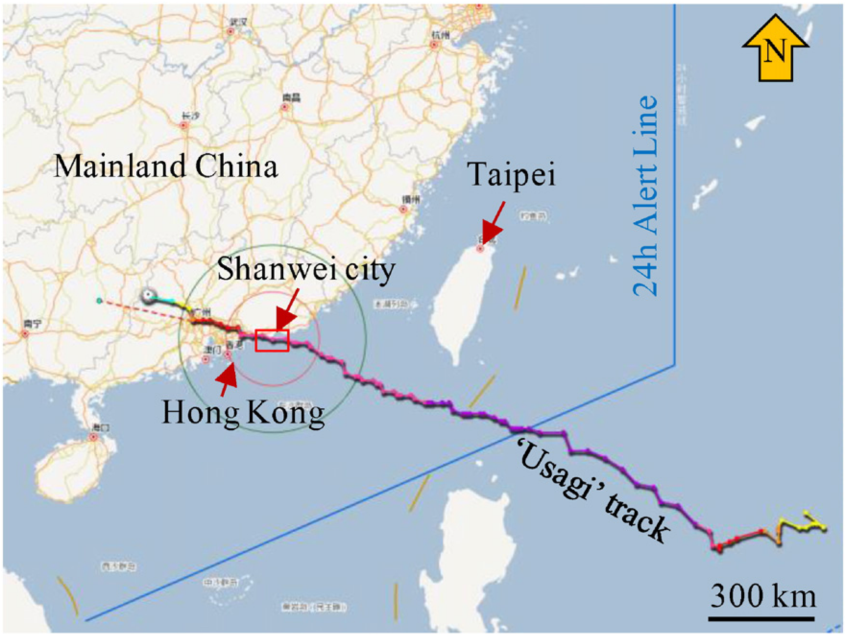

Fig. 1. The track of super typhoon Usagi.

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