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Short communication

Structural failure simulation of onshore wind turbines impacted by strong winds

Jui-Sheng Chou[a,*], Yu-Chen Ou[b], Kuan-Yu Lin[a], Zhi-Jia Wang[a]

[a] Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan
[b] Department of Civil Engineering, National Taiwan University, Taipei, Taiwan

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ABSTRACT

The renewable energy industry is thriving in many countries against a global backdrop of growing environmental awareness. In particular, in Taiwan, wind is emerging as a potential source. The Taiwanese government has implemented the “Thousand Wind Turbines” project as a collaboration with the private sector to construct a wind power infrastructure. However, when Typhoon Soudelor hit Taiwan on August 7–8, 2015, the towers of 2.0 MW wind turbines close to Taichung harbor collapsed and falling blades damaged one of the collapsed turbine towers. This incident of wind turbine collapse was the second in the nation and was more extensive than the previous one. This study investigates the causes of this incident and the mechanical mechanisms of turbine tower collapse and blade fracture to support risk prevention and hazard-resistant design of future wind turbines. Relevant data are obtained to simulate wind turbine collapse. Next, mechanical analyses via finite element method are carried out to identify mechanisms of failure and structural weakness planes, with the ultimate purpose of summarizing potential causes of collapse. Improvement solutions on strong wind resistance of wind turbine towers and their benefits are discussed. Finally, this study gives the recommendations on weaker blades being a safety mechanism for the wind turbine tower, torque capacity of the pitch system as well as the required strength of joint bolts to be installed in steel structural connections, so as to withstand severe storms.

1. Introduction

This study focuses on a wind farm in Taichung in central Taiwan, whose Z72 wind turbines (2.0 MW) collapsed between August 7 and 8, 2015, as a result of Typhoon Soudelor. The maximum instantaneous wind speed, measured by the supervisory control and data acquisitions (SCADAs) in the nacelles of the turbines, exceeded 59.5 m/s. In the wake of the typhoon, a maintenance team that was sent by the owner of the wind turbines found that one wind turbine's blades were fractured and six towers of turbines had snapped at either the first or second of the three sections from the ground.

In this study, data from in-situ inspections, technical information from the manufacturer, and the results of a literature review are utilized to develop a wind turbine model, simulate the crumbling of turbines, and conduct forensic engineering assessments, to identify mechanisms of the collapse of turbines and weak planes in the tower to determine the causal factors of the incident and inform the construction, hazard-resistant design [1], and risk prevention planning of future wind turbines.

Fig. 1 depicts the geographic locations of the wind turbine units that were damaged by Typhoon Soudelor. They were located in the northwest of the Taichung port area, approximately 3 km south of the Dajia River estuary.

A loss-making incident may occur as a result of multiple factors. All of the inspection items that were covered by the incident investigation were organized into a flow chart (Fig. 2). This investigation comprised the following steps: (1) collecting data on wind turbine construction and typhoon-induced turbine collapse and reviewing these data to identify the causals of the turbine collapse incident and conduct in-situ simulations; (2) conducing a finite element analysis (FEA) of forces on the wind turbines in the ultimate limit state, identifying or excluding potential causal factors; and (3) determining the causes of the incident and proposing improvements to the turbines.

The rest of this paper is organized as follows. Section 2 reviews wind turbine accidents and incidents worldwide. Section 3 investigates relevant documents including the proof strength, design strength, and specifications of bolts, the manufacturer's blueprints of the wind turbines, the construction and maintenance of the turbines and possible causes of the incident. Section 4 presents a structural analysis (which consists of a series of force analyses of wind turbines under various

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* Corresponding author.
E-mail addresses: jschou@mail.ntust.edu.tw (J.-S. Chou), yuchenou@ntu.edu.tw (Y.-C. Ou).

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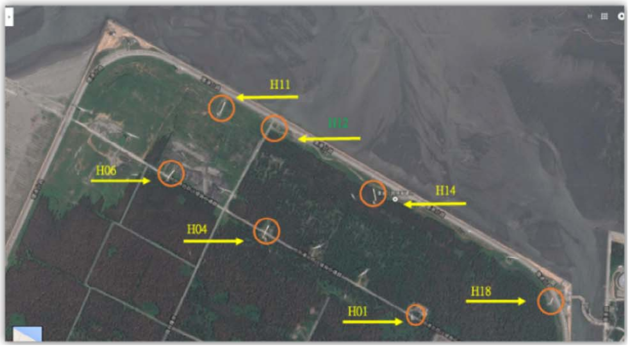
Incident site

Satellite image (before turbines collapsed)



Satellite image (after turbines collapsed)

Fig. 1. Locations of damaged wind turbines (https://www.google.com.tw/maps/).

structural failure sequences and scenarios), and summarizes the results of the investigation into the turbine collapse incident and its causal factors. Section 5 provides suggestions concerning hazard-resistant design and risk prevention planning.

2. Literature review

Reports on the investigations of relevant incident and forensic engineering assessments of disaster-damaged wind turbines in Taiwan [2–4] and other countries [5–8] were reviewed to identify the potential causal factors of the turbine collapse incident.

2.1. International case study

Table 1 presents the extent of damage to wind turbines that collapsed during typhoons [3,4,6,8–10]. Previous cases have shown that wind turbines with damaged blades can retain their respective towers [9]. The FEA has been used to illustrate the failure mode of Z72 tower structure, and identify the tower bolt junctions of a Z72 wind turbine as its weak planes [4].

An investigation of the effect of rainfall and wind speed on wind turbines revealed that rainfall has a negligible effect on them, accounting for 1–3% of wind load [7]. The highest rainfall ever recorded near the damaged wind turbines under investigation is 87.5 mm/hr at a weather station in Wuqi District in Taichung; on the basis of [7], the analysis in this study omits the effects of rainfall.

2.2. Statistics concerning wind turbine-related accidents and incidents globally

A total of 1376 wind turbine-related accidents and incidents worldwide, from 2006 to the end of March 2016, compiled by the Caithness Windfarm Information Forum [11] were reviewed to analyze the causal factors of the Port of Taichung turbine collapse incident and the risk factors that may have contributed to turbine damage.

The majority of the identified cases were categorized as "Others" (n = 306, 22% of all the cases), meaning that damage was unspecified or negligible, investigation reports were not published, or causes were not determined. Excluding such cases, the total number of wind turbine-related accidents and incidents was 1070, of which 23% involved "damaged blades" and 11% "damaged structures" (Fig. 3). Fig. 3 presents causal factors in the collapse of wind turbines and their respective frequencies worldwide during 2006–2016.

A previous study [12] estimated the failure frequencies of the components of onshore wind turbines and subsumed these components under 16 subassemblies. Towers had the highest failure frequency (0.151 times per year), followed by gearboxes (0.134 times per year) and rotor blades (0.124 times per year). The average failure frequency (caused by component fault or damage) of onshore wind turbines was estimated to be 1.22 times per year. In the Port of Taichung incident, the blade-pitch systems of the wind turbines were damaged, causing a chain of effects that eventually induced the collapse of the towers.

3. Data collection and incident investigation

Data on Z72 wind turbines were obtained from the owner of the turbines to ensure the reliability of upcoming analyses. Relevant data were also derived from other credible sources to ensure comprehensiveness of the data and ensure the objectivity of the analysis of the collapsed turbines.

3.1. Recorded operating data of wind turbines

Operating data were collected from July 1 to August 15, 2015, for the damaged turbines in the Port of Taichung. The operating data of the turbines before collapse, which were obtained through the SCADA system [13,14] in each of the turbines, included wind speed, wind direction, rotor speed, yaw angle, blade rake, and turbine condition.

Table 2 shows the conditions of the wind turbines before and during collapse, which were inferred from the data on turbine operations, in-situ inspections, and interviews with on-site engineers. Note that the SCADA systems neither directly measured blade conditions nor revealed irregular patterns prior to blade breakage [15].

3.2. In-situ wind speed during the typhoon

Table 3 presents the maximum instantaneous wind speed of each collapsed turbine, which was estimated from recorded wind speed data.