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Post-mortem study on structural failure of a wind farm impacted by super typhoon Usagi

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1. Introduction

Super typhoon Usagi, which was on category 4 according to the Saffir-Simpson hurricane intensity scale [1], impacted a wind farm near Shanwei city on the southeast coast of China in 2013, see Figure 1. During typhoon impact, the wind farm experienced a dramatic change of wind direction and a maximum wind speed (3s average) of 57 m/s at a 10-m elevation. As a result of this super typhoon, eight turbine towers collapsed, eleven rotor blades broke off and three turbines were burned, leading to an approximate $16 million loss to the wind farm.

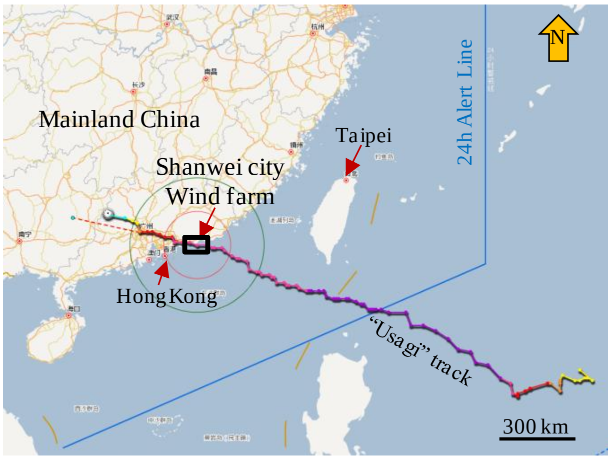

Figure 1 Super typhoon Usagi and wind farm location

Authors of this paper carried out a post-mortem study on the wind farm with particular focus on the tower collapse and blade failure. A systematic procedure was developed for this endeavor by integrating both aerodynamic analysis for wind characterization and structural analysis for towers and blades. To provide necessary input for the procedure, data of local wind record, terrain topography and turbine status were collected, analyzed and assessed together with field investigation and user inquiry. Through this study, plausible root-causes of structural failure of the wind farm were indentified.

This paper summarized the process and key findings of structural failure investigation on the wind farm impacted by super typhoon Usagi. It is expected that insights gained from this study could assist structural failure mitigation of wind farms under extreme wind conditions.

2. Approach

The proposed procedure for the post-mortem study on structural failure of the wind farm is shown in Figure 2. The wind profile along the turbine height was estimated based on meteorological data and the typhoon wind model suggested by [2]. Wind load acting on the wind turbines was then calculated considering turbine positions at an emergency stop state and the terrain effect of the wind farm which was numerically reconstructed in a three dimensional model using Global Positioning System (GPS) data. Computational Fluid Dynamics (CFD) simulation was followed to capture wind characteristics of the concerned wind farm terrain under typhoon impact.

Meanwhile, structural models of tubular steel towers and composite rotor blades were established according to the information obtained from turbine specification, design documents, user inquiry as well as field investigation. Nonlinear Finite Element (FE) analysis was then carried out to investigate structural response of the towers and the blades at different stop positions of wind turbines. Numerical prediction was compared to post-mortem observation regarding failure mode, failure location and the corresponding load level. The essential factors affecting structural failure were examined and plausible root-causes of tower collapse and blade failure of the wind turbines were indentified accordingly.

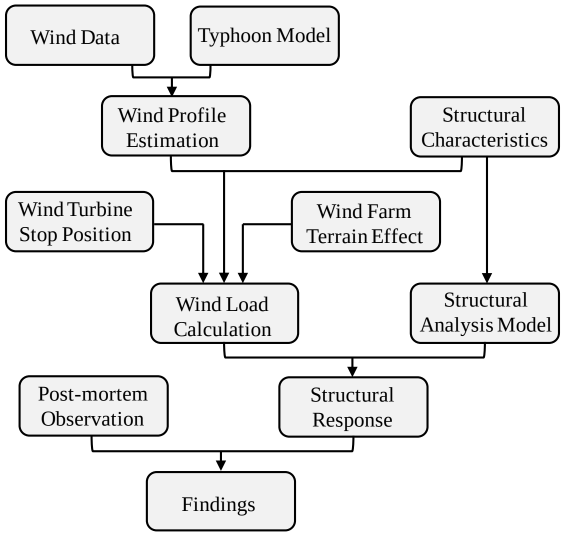

Figure 2 The proposed procedure for the post-mortem study

3. Main body of abstract

3.1 Post-mortem observation

Field investigation on the wind farm was conducted after Usagi impact. Representatively, an overview of structural failure is shown in Figure 3. Failure statistics showed that eight out of twenty-five towers collapsed, three out of twenty-five turbines were burned and eleven out of seventy-five blades fractured. For the latter, the number of the fractured blades would be thirty-five if the blades installed on the collapsed towers were taken into account, leading to 46.7% blades failed in the wind farm.

Figure 3 An overview of structural failure of the wind farm (with turbine manufacturer’s logo removed)

It was found that all tubular steel towers failed due to local buckling and the collapsing direction was SW or SSW, suggesting the dominating wind load coming from NE or NNE. The composite blades fractured at a location ranging from the inboard to the middle span, where the load-carrying box-beams inside the blades were totally fractured. Severe cracks were also found at sandwich shells of the blades which did not break off.

Interestingly, the distribution of structural failure over the wind farm appeared to be strongly relevant to the terrain characteristics. Six out of eight collapsed towers were found on the flat valley floor while most towers located on ridges with higher elevations remained intact. On the contrary, most blade breakage occurred at the turbines located on ridges rather than on the valley floor.

3.2 Wind load calculation

Using GPS data, the three dimensional topographic model of the wind farm terrain was constructed and it was further used in CFD simulation to study wind characteristics at local site of each turbine. The local grids of CFD model of the terrain are shown in Figure 4. Wind speed and turbulence intensity distribution along the turbine height were calculated for different wind directions with the maximum wind speeds recorded during Usagi.

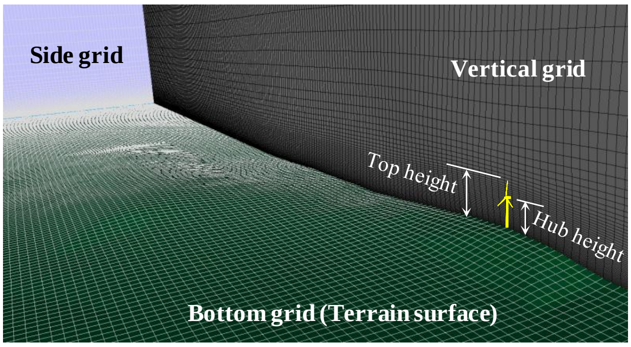

Figure 4 The local grids of CFD model of the wind farm terrain

Considering the emergency stop state of the wind turbines during typhoon impact, the design code [3], which are well-established for wind pressure calculation of high-rising civil structures, were used to predict wind load of towers, nacelles and blades using wind speed profiles obtained from CFD simulation. Topographic locations and stop positions of the turbines were considered in the calculation.

3.3 Structural analysis

Tubular steel towers and composite rotor blades were reconstructed numerically by shell elements in FE models according to turbine documents and field data. Nonlinear analysis was then performed to investigate structural response with distributed wind loads. For the blades, Tsai-Wu criteria [4] was used to determine the failure occurrence of unidirectional composite materials in the load-carrying box beams. The location of blade failure was predicted to be in reasonable agreement with that observed in the field. For the towers, local buckling due to steel yielding was predicted to initiate at a tower height where a rapid reduction of wall thickness existed, and this finding agreed well with the post-mortem observation.

Furthermore, it was found that even at a hub-height wind speed well below the extreme design wind speed, i.e., 70 m/s, the towers could experience steel yielding and local buckling in case of an unfavorable stop position, at which rotor blades and nacelle had maximum cross-sectional areas facing against wind. It is worthy noting that the tower collapse should not have occurred regardless of the turbine stop position as long as the wind speed does not exceed the extreme design speed, as the unfavorable stop position is one of the loading cases in wind turbine design. The analysis implied a possible design defect associated with wall thickness of the towers. When a favorable stop position was under concern, it was found that a hub-height wind speed of 76 m/s, which corresponded to a wind speed of 57 m/s at a 10-m elevation, was not able to cause damage to the tower, suggesting the significance of the stop position of the turbines during typhoon impact.

4. Conclusion

From this study, it was found that high wind speed during super typhoon Usagi was the main reason for the destructive structural failure of the wind farm. Nevertheless, turbine position at an emergency stop state also played an vital role for the tower collapse and blade breakage due to dramatic change of wind direction during typhoon event. The complex terrain showed high possibility to adversely affect the turbines by increasing wind fluctuation which consequently increased fatigue load of the turbines. The study also suggested that the towers collapse might associate with design defect, and the rapid reduction of wall thickness near the bottom of the towers needs to be modified in order to prevent local buckling which was predicted to occur at a load level well below the extreme design load according to the original design.

5. Learning objectives

After reading this paper, the reader will be able to:

- gain insights into structural failure of a wind farm under extreme wind condition.
- identify the important factors affecting structural failure of a wind farm.
- implement a systematic procedure to structural failure investigation of a wind farm.
- understand the significance of turbine stop position and terrain effect on turbine failure.

6. References

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Declaration

The paper is intended only for academic research purpose. The name of the turbine manufacturer and the technical information of the turbine would not be disclosed in the paper or during the presentation.