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Structural performance of a parked wind turbine tower subjected to strong ground motions

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ABSTRACT

The objective of this paper is to evaluate the structural performance of a typical wind turbine tower subjected to strong ground motions. A detailed finite element model of an 80 m wind turbine tower was developed and subjected to strong ground motions. Two sets of input ground motions were used: one with pulse-type near-fault motions and the other one with far-fault motions. The structural performance of the wind turbine tower was investigated through seismic fragility analysis. The potential limit states were defined as global buckling of the tower, first occurrence of yielding, overturning of the foundation and permanent deformation of the tower. It was found that the wind turbine tower investigated in this study is most vulnerable to the overturning in the event of an earthquake. Yielding of the tower is the second most probable failure mechanism, which is followed by development of permanent deformation and global buckling of the tower. Similar trends in the failure mechanism were observed for both near-fault and far-fault ground motions.

1. Introduction

The use of wind energy is increasing rapidly, and the worldwide wind capacity has exceeded the 300 GW milestone in 2013 [1]. Many wind turbines are constructed in earthquake prone areas. For example, the 1986 North Palm Springs Earthquake and 1992 Northridge Earthquake occurred near the utility scale wind turbines [2]. The research on seismic analysis of wind turbines is comparatively new. In the past, seismic analysis of wind turbines largely utilized existing building codes. The process involves calculating horizontal seismic force using building codes and then superimposing the load with operational turbine load [3]. The site specific seismic analysis by Agbayani [4] used seismic loading based on Uniform Building Code [2,5]. Guidelines, standards developed by various organizations, committees and manufacturers in order to improve the overall safety and performance of wind turbines are based on established methods such as response spectrum analysis and time history analysis [6–8].

Although building codes are employed in analyzing the wind turbine towers, their design goal and structural characteristics are different from the buildings. First, while modern buildings are designed to develop inelastic deformation during design-level earthquake, the design goal of the wind turbine is to minimize interruption in reliable operation. Wind turbines have mechanical components such as shafts, links, bearings and gears, which are critical in generating the electricity. These components should function normally after the earthquake. To ensure the normal operation, wind turbines should satisfy Serviceability Limit States (SLS) [8] such as the tilt at the tower top. Second, wind turbines have longer natural period compared to a building of the same height. The mass at the tower top (nacelle and rotor) could be as large as the mass of the entire tower, which leads to long natural period. Considering the differences in structural characteristics between wind turbine towers and buildings, it is necessary to understand the structural performance of wind turbine towers when they are subjected to strong ground motions.

The earthquake loads, broadly categorized as near and far fault loads, exhibits different characteristics and induces different behavior in the structure. The response of the structures due to near, far fault earthquake loading was studied by various researchers [9–17]. The studies were performed to quantitatively identify [18] and to characterize [19] the near fault ground motions. The relation between near fault rupture directivity pulse and the earthquake magnitude [20] was studied to present the preliminary model for acceleration response spectra of neat fault fault-normal ground motion.

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Fragility is the probability that a system exceeds a certain limit state under the action of load, and has been used to estimate the response of the structures. It is customary to quantify the fragility as a function of peak ground acceleration (PGA) or spectral acceleration. The analytical method [21], analytical fragility function fitting [22] were proposed to evaluate the performance of the structures. The fragility curves were used to assess the vulnerability, collapse risk [23,24], damage of moment connections [25,26]. The various studies were performed by using fragility methods [27–30] to evaluate the performance of the structures.

Many instances of wind turbine failure were recorded in the recent past. Refer Table 1. Although, the recorded wind turbines failures due to earthquakes are rare, due to the scarcity of the event, the wind turbine towers subjected to earthquake loads are expected to fail. The failure of wind turbines could disrupt the normal operation of the whole wind farm for considerable time. This is the concern to wind energy developers, insurance companies, and demands the performance evaluation of the wind turbine tower structures constructed in the earthquake prone region.

The objective of this paper is to investigate the structural performance of a typical wind turbine tower against near fault and far fault earthquake loading. In doing so, special attention will be made for the serviceability limit states unique to wind turbine, as well as other common failure limit states. Fragility curves will be developed to compare the near fault response and the far fault response. The tower will be modeled using three-dimensional finite elements because the tower response is sensitive to fine details of the tower such as the door or the connection flanges.

2. Literature review and identified research need

2.1. Seismic analysis of wind turbine tower

The seismic analysis in time domain was studied by Ishihara and Sarwar [37] by developing full scale nonlinear model of wind turbine, and the semi theoretical formula was developed. The soil structure interaction [38,39] and aerodynamic damping [40] were found to affect the dynamic response of the wind turbine tower. Full scale shake table test was performed to characterize the seismic response of a 23 m tall wind turbine tower [41]. A simplified multi degree of freedom model with the lumped masses and refined finite element models were studied in order to analyze the seismic response of a wind turbine tower [42]. At critical locations, refined finite element model gives accurate results for static and buckling analysis. The simplified model exhibits relative accuracy for critical load corresponding to local buckling subjected to seismic loading. Response of an 80 m tall wind turbine under Canadian seismic environment was also studied [43]. Fragility analysis was conducted for steel and concrete wind turbine towers, using the tower tip displacement as the limit state parameter [44]. The seismic loading analysis was studied by Prowell et al. [45] for National Renewable Energy Laboratory (NREL) 5 MW wind turbine considering idling, operating and emergency shutdown scenarios. The authors [45] found that tower moment demand is an important parameter while designing the wind turbine tower in seismic zones. The importance of appropriate damping to evaluate the response to the near-fault excitation of wind turbine tower by considering the soil structure interaction was studied by Stamatopoulos [46]. The aerodynamic damping in lateral and along wind direction was studied [47] to compare the stresses due to combined loading due to operational, seismic loads, and the stresses due to extreme wind loads.

2.2. Original contribution of the paper

The literature review shows that further research is needed in understanding the seismic performance of the wind turbine tower. Most of the past studied were based on a limited number of earthquake records. Therefore, findings from these studies cannot be generalized as the typical failure mechanism of the wind turbine tower. Another area of improvement is to use a rigorous approach in estimating the failure probability. While some studies did estimate the failure probability, they used simplified approaches. An accurate estimation of failure probability also has a practical benefit. This makes it possible to estimate the number of wind turbines that would fail in a wind farm for various earthquakes.

In the following, relevant literature will be reviewed focusing on the original contribution of this paper: (1) comprehensive earthquake records including near fault and far fault motions, and (2) fragility estimation based on the capacity, the demand, and their uncertainties. In turn, we seek to better understand the failure mechanism of an 80 m wind turbine tower.

3. Tower modeling and verification

The wind turbine tower used in the present work was modeled after the VESTAS 1.65 MW model. The tower model was simplified by using the equivalent mass for nacelle and rotor assembly. Such simplification was shown to be accurate when lower modes govern the seismic response [41]. On the other hand, the tower was represented using a high-fidelity finite element model, following three-dimensional details such as the flange and the door. Such fine modeling details were shown to be important especially when the failure occurs around these locations [43].

The tower model accurately describes a wind turbine with stationary blades, such as a wind turbine under maintenance, or a wind turbine under the cut-in speed (typically about 5 m/s). This model has both conservative and unconservative aspects in seismic response, when compared to a wind turbine with rotating blades. It is conservative in terms of the damping in the seismic analysis. When the blades are rotating, they add about 5% aerodynamic damping in the fore-aft direction [40]. The model used in this study does not have aerodynamic damping and therefore is conservative. On the other hand, it is unconservative because it does not consider the forces due to the rotating actions of the blades. If necessary, the total response can easily be estimated by using the superposition [3]. Integration of the blade rotation and seismic action is outside the scope of this study. This study is focused on quantifying the response of the wind turbine with stationary blades subjected to near fault and far fault ground motions.

Table 1
Wind turbine failure examples.

Wind Turbine at	Failure	Ref.
Ellenstedt, Germany, 2002	Foundation overturning due to hurricane load	[31]
Hornslet, Denmark, February 2008	Uncontrolled blades rotation speed resulted in blade hitting the tower	[32]
Searsburg, Vermont, US, 2008	Excessive blade deflection resulted in blade hitting tower	[33]
Wyoming, Arlington, US, 2011	Combination of cold weather, and high wind speed resulted in tower bending at bottom	[34]
Fenner wind farm, Madison County, New York, 2009	Failure reason not released by company	[35]
Fayette County, Pennsylvania, 2014	Failure reason not known	[36]