Evaluation of the Seismic Vulnerability of Tubular Wind Turbine Towers

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SUMMARY:

The presence of attractive wind resources in high seismic regions, such as California, has resulted in an increase in the number of wind turbine installations in such areas. An obstacle to this growth, however, is the challenge of obtaining the necessary financial backing that is usually tied to onerous insurance requirements against seismic damage. One of the key reasons for the severe insurance requirements, which can be as high as requiring insurance cover for the total replacement value of the entire wind farm installation, is that the seismic risk to wind turbines has not been studied rigorously and accordingly there is a tendency to default to an extreme conservative position. While there is extensive analytical and empirical information on the seismic vulnerability of buildings and other common structures, similar information does not exist for wind turbines. Wind turbine installations have not experienced severe ground shaking, given the only recent increase in installation of such turbines in high seismic regions, and the analytical basis is also sparse with the focus more on the operational aspects of the wind turbines as opposed to their seismic performance. The design standards of these turbines are also often controlled by aspects outside of seismic considerations. Complicating this further is the fact that the seismic risk to wind turbines is distinct from other common structures for a variety of reasons including a lack of redundancy within the structure and within the wind farm installation. This paper highlights several pertinent issues unique to assessing seismic wind turbine vulnerability and also presents finite element analysis results on the fragility of one particular wind turbine tower as a function of ground motion intensity and frequency content. A finite element model of an 80m tall 2.4 MW turbine tower is developed, which is subjected to nonlinear dynamic analyses utilizing suites of ground motions representing near-field conditions, soft-soil conditions, and standard conditions. The response of the tower is quantified and fragility functions for a severe damage state are presented.

Keywords: Horizontal Axis Wind Turbines, Seismic, Vulnerability, Collapse

1. INTRODUCTION

The wind energy industry continues to grow quickly throughout the world. At the end of 2011, worldwide wind energy nameplate capacity totaled nearly 240 GW, almost double that from only three years prior (WWEA, 2011). Approximately half of this installed capacity is in the European Union and about 20% is in the United States. Other countries, such as China and India, are fast expanding their wind energy production capacity. With the added focus on developing renewable energy sources, the growth in the wind energy industry is expected to accelerate.

Recent wind turbine design standards (including Risø, 2001; GL, 2003; and IEC 2005), which are typically applied in low seismic areas like Northern Europe, have not focused on seismic design principles. As suggested in these guidelines, there are few locations in the world where seismic *design*

loads will exceed those from wind. However, an increasing number of wind farms have been and are being installed in locations with higher seismicity, including parts of North America, Asia, and Southern Europe (Figure 1).

Even in these locations, the wind *design* loads may still exceed the seismic *design* loads, but, during rare earthquake events, the potential exists for these turbines to experience forces well in excess of these design level forces leading to unsatisfactory performance of these turbines. From a seismic risk assessment perspective it is therefore critical to understand and quantify the *response* of wind turbines to seismic ground shaking that may be associated with these severe earthquake events. This response is particularly sensitive to catastrophic losses because:

- Modern wind turbines, unlike buildings and most other common structures, exhibit no redundancy in the structural system. Thus, if any section of the structural system becomes sufficiently damaged, then the entire turbine is susceptible to collapse, as shown in Figure 2 (note that this figure shows damage to a wind turbine tower under wind forces; to the best knowledge of the authors, no such examples exist for seismic loading).
- Wind farms are typically comprised of many turbines with similar characteristics, for instance all manufactured by the same manufacturer, similar heights, similar foundation designs, etc. Thus, a single seismic event with unfavorable ground motion characteristics could potentially damage most of the turbines at a particular wind farm. This is in contrast to buildings in a city, which have diverse structural systems, dynamic characteristics, and redundancies that limit the potential of any single seismic event to unfavorably affect all buildings.

For many types of structures, the seismic risk can be quantified through a combination of historical data on the seismic response of the structure and engineering analysis. However, because modern wind turbines have only been built recently and are largely concentrated in regions with low seismicity, they have not been subjected to any significant levels of earthquake ground shaking, and there is little to no reliable information on the actual seismic performance of these structures, especially under severe but infrequent ground shaking. Two exceptions are the 1994 Northridge Earthquake (magnitude 6.7) and the 1986 North Palm Springs Earthquake (magnitude 6.1), which induced low to moderate ground shaking at two wind farms (nearby measuring stations recorded peak ground accelerations of 0.06g and 0.33g, respectively). In both cases, however, there were no reports of damage to the wind farms. As a result of the limited data, seismic risk to modern wind turbines must be assessed through analytical or experimental approaches. This topic has not been studied extensively, however there are some notable prior analytical studies (Nuta, 2011; Bazeos, 2002; Lavassa, 2003) and experimental studies (Prowell, 2009).

Figure 1. Example of a modern wind turbine farm in California.

Figure 2. Example of collapse of wind turbine under wind loading. (Source: **http://www.greenward-technologies.com/iso-e.htm**)

2. WIND TURBINE STRUCTURE

While wind turbines have been in use in some form or another since the late 1800s, this paper focuses on modern, horizontal-axis wind turbines (HAWTs) with three blades, the predominant wind turbine type in the world today. As shown schematically in Figure 3, the modern turbine is comprised of four primary components:

- Foundation, which is often constructed of reinforced concrete and may be a mat or pile system
- Support tower, which is the structural system for the turbine
- Rotor, which is comprised of the rotating turbine blades
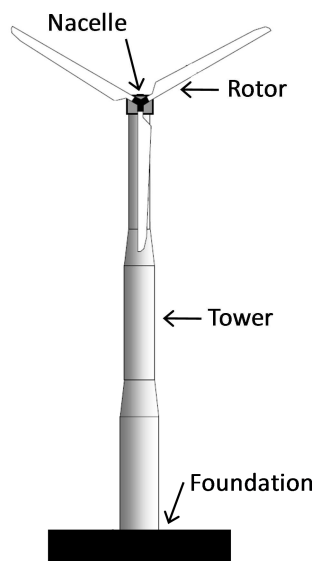- Nacelle, which houses the electrical and mechanical equipment

Figure 3. Schematic of modern wind turbine. (Base Image Source: Nuta, 2010)

While each of these four components is vulnerable to seismic damage, this paper focuses only on the evaluation of the seismic vulnerability of the support tower. The support tower for most HAWTs is

made from steel and has a circular cross-section. The diameter and thickness of the hollow tower cross-section vary along the height of the turbine. The tower walls are typically quite slender. For example, one particular cross-section of a widely-installed wind turbine has a maximum diameter to thickness ratio (D/t) of nearly 300. These sections are far more slender than anything commonly employed in buildings (e.g. the largest slenderness ratio for a round HSS section in the AISC manual is 69) and exceed the slenderness limits for classification as a slender cross section as defined by the AISC Specification ($D/t > 178$ under pure bending and $D/t > 64$ under pure compression for 50 ksi steel) and Eurocode 3 ($D/t > 60$ under pure bending and pure compression for 50 ksi steel).

Figure 4. Example of cross-section of a wind turbine tower shows high slenderness ratio.

Because these sections are so slender, an assessment of the vulnerability of a particular wind turbine to seismic loading should include a characterization of local buckling initiation and post-buckling response of the cross-sections of that turbine. Analytical assessment of local buckling initiation and post-buckling response is particularly challenging because these types of sections, which characteristically have dozens of elastic buckling modes all with nearly identical buckling loads, are widely known to be acutely sensitive to imperfections such as geometric imperfections, residual stresses, material inhomogeneity, boundary conditions, and eccentric loadings (Schmidt, 2000; Teng, 1996). For example, consider the elastic buckling analyses in Figure 5. These images show the first, fourth, eighth and sixteenth local buckling modes and the corresponding buckling loads for an 80m tower loaded transversely at the tower top by load V. For this case, the critical buckling load, V_{cr}, between the first and sixteenth modes differs by only 33% (the buckling load for the first 50 modes differs by only 40%), which is a strong indicator that a structure will be highly sensitive to initial imperfections.

The stability of slender circular sections is also sensitive to the interaction of axial and shear stresses (Winterstetter, 2002; Gettel, 2007; Schneider, 2007). For example, the mode shapes in Figure 5 clearly show modes that have axial (Modes 1 and 8), shear (Mode 8) and mixed (Mode 16) character. The complicated and interactive effects of combined loading (axial plus shear) and imperfections underscore the challenges with analytically assessing the performance of slender circular shells. Typically, such assessments require physical tests for validation. The authors are participating in ongoing research into analytical and experimental methods for assessing local buckling strength and post-buckling response in wind turbine towers. In the current paper, the issue is circumvented by assuming that the towers locally buckle and collapse upon cross-sectional loading equal to the yield moment. This assumption is supported somewhat by Nuta (2010) who presents analytical results for the moment-rotation response of a slender cylindrical shell (D/t =286; D = 2.0m) with two constitutive models representative of structural steel and subjected to pure flexure. Under those conditions, the

section locally buckled at a moment 2.4% greater than the yield moment for the first constitutive model and 7.0% greater than the yield moment for the second constitutive model. In both cases, the response showed a steeply negative post-buckling slope, a characteristic that indicates a high degree of sensitivity to imperfections (Koiter, 1966).
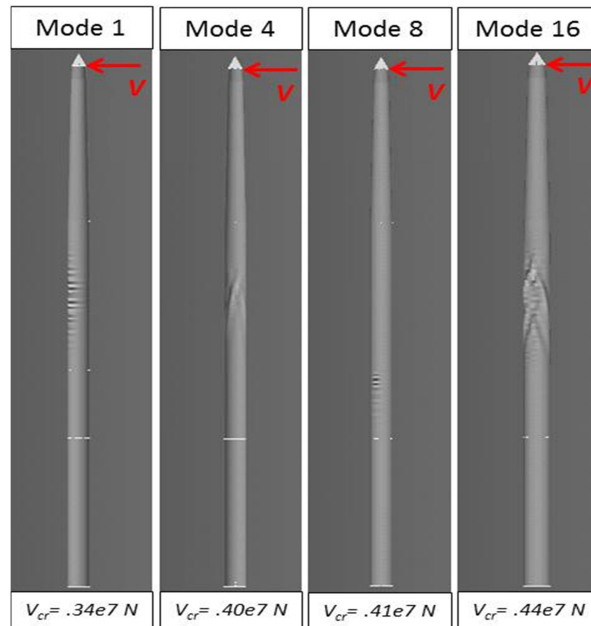

Figure 5. Elastic buckling modes and corresponding loads for an 80m tower under a transverse load applied at the tower top.

3. DYNAMIC CHARACTERISTICS OF TOWER

The typical geometry (Figure 3), construction material (steel), and mass distribution (high concentration at the top because of the nacelle and rotors) of tall, modern wind turbines make these structures quite flexible. For example, the fundamental periods of two 80m tall wind turbines (turbine design was from different manufacturers) were calculated to be between 2.9 and 3.5 seconds, comparable to that of a modern 20–30 story steel building.

The long period of these tall wind turbines is beneficial from a seismic vulnerability perspective because the energy content of *standard* ground motions tends to be rather limited in this range. However, the characteristics of ground motions can vary substantially from one site to another and some ground motions, such as those that can occur near a fault—which can cause "pulse-like" ground motions (Somerville et al., 1997 and Chioccarelli and Iervolino, 2010)—or at sites with soft soils (Ruiz-Garcia and Miranda, 2006)—which can amplify the ground motion—can pose a greater risk to wind turbines. Figure 6 shows three ground motion time histories, all of which have similar peak ground acceleration, but significantly different frequency characteristics.
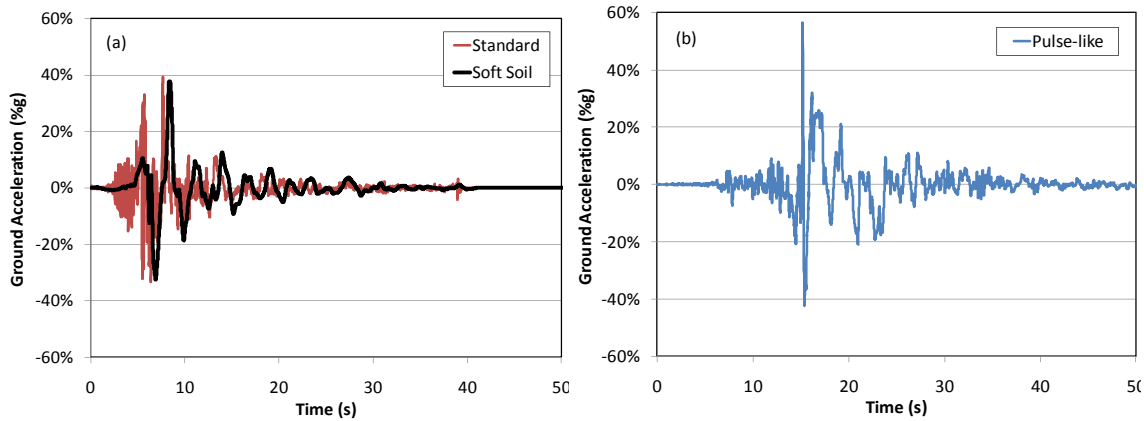
Figure 6. Example of ground motion time history for (a) standard and soft soil, and (b) pulse-like

Another important factor when considering the dynamic response of wind turbines subjected to seismic shaking is the damping, or the ability to dissipate energy during structural vibrations. The magnitude of the damping varies depending on whether the turbine is operational (with the rotors spinning) or parked. Spinning rotors provide an additional aerodynamic mechanism for energy dissipation, and wind turbine damping has been estimated at about 5% of critical for this operational condition (Wichter, 2005). The damping for a parked turbine is substantially less and has been measured experimentally (Prowell, 2009) and predicted analytically (Bazeos, 2002) to be roughly 0.5% of critical.

Industry guidelines (IEC, 2005) currently suggest a value of 1% of critical for a parked turbine. It is common for modern wind turbines to include emergency control systems that shut down the rotors when a nacelle acceleration of 0.1g is measured. The difference in damping between operational and parked conditions can significantly influence the response of a wind turbine to seismic shaking, and thus, it is important to assess the risk both in an operational and in a parked condition. While the additional damping is helpful in reducing potential adverse response, the additional wind load sustained by the turbine in the operational state adds to the load that the turbine must transfer safely to the ground during seismic loading. This is a topic currently under investigation by the authors. In the current study, we assume structural damping equal to 1% of critical.

4. STRUCTURAL MODEL AND VULNERABILITY

This study has investigated the vulnerability of two 80m tall, 2.4 MW wind turbine under suites of ground motions with various characteristics; for brevity only the results for one of the turbines are presented in this paper. The vulnerability of each turbine is assessed using detailed nonlinear finite element models, which capture the unique dynamic characteristics of each turbine. The nonlinear model was constructed using the structural engineering analysis program SAP2000, which was validated against a more complex finite element model built using ABAQUS.

Incremental dynamic analysis (Vamvatsikos and Cornell, 2002), where the response metrics are assembled using a predefined set of ground motions scaled to varying levels of ground motion intensity, was used to establish a probabilistic view of the wind turbine's structural response to dynamic earthquake loads. At each intensity level, the probability of severe damage, which in this study is taken to occur when any cross-section along the tower height reaches the yield moment, was computed by taking the ratio between the number of ground motions producing a moment higher than the yield moment to the total number of ground motions in the set. By doing this at various intensity levels, a fragility relationship between the probability of severe damage as a function of ground motion intensity is established. Three sets of twenty ground motions were used to establish these fragility relationships for different sets of conditions, which are as follows:

1. Firm Soil Set: the NISEE 10% in 50 year ground motion set for Los Angeles developed for the SAC Steel project (SAC, 1997)
2. Pulse-like Set: the PEER set of pulse-like ground motions developed by Baker (2011)
3. Soft Soil Set: the NISEE soft soil ground motion set for the Los Angeles area developed for the SAC Steel project (SAC, 1997)

Figure 7 presents the vulnerability of the considered turbine. The figure indicates the probability of severe damage (in this context, severe damage corresponds to any cross-section of the turbine reaching the yield moment) as a function of the peak ground acceleration at the site. Three different curves are shown: the first shows the probability of severe damage for a set of "standard" ground motions, the second for a set of "pulse-like" ground motions on firm soil, and the third for a set of "soft soil" ground motions.
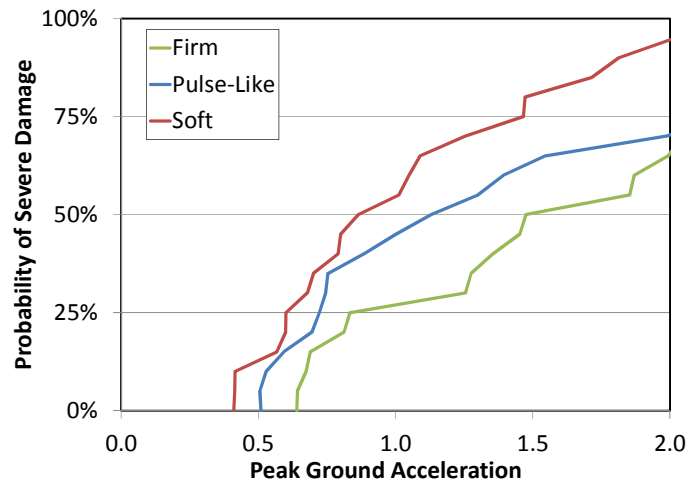

Figure 7. Fragilities for an 80m 2.4 MW wind turbine subjected to "standard", soft-soil, and "pulse-type" ground motions.

The effects of the ground motion characteristics are significant. For example, the peak ground acceleration, for parked conditions, corresponding to a 50% probability of severe damage is 70% higher for standard ground motions than for soft soil ground motions and 30% higher for standard ground motions than for pulse-like ground motions.

To evaluate the effect of design characteristics on the vulnerability of the wind turbines, another 80m tall wind turbine, manufactured by a different company, was evaluated similarly to the wind turbine discussed previously in this paper. The two turbines are identical in height, but different in capacity, support tower geometry, and steel grade. The fragility for the two wind turbines are compared in Figure 8. For these two turbines, the peak ground acceleration corresponding to a 50% probability of severe damage differs by about 16%, which is significant, particularly in the tail portions of a seismic hazard curve.
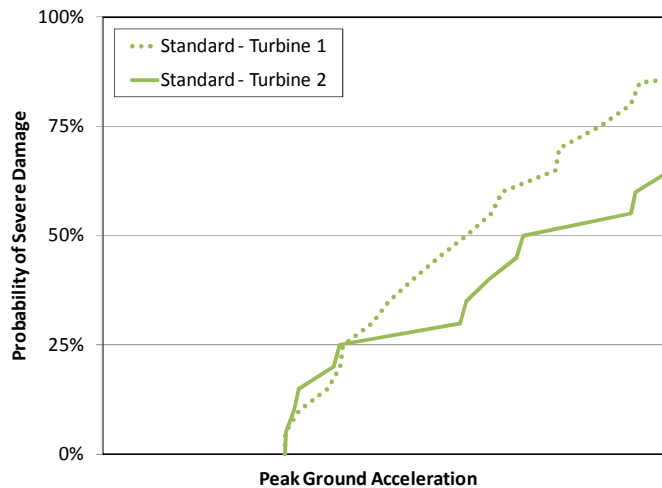
Figure 8. Fragilities for two 80m wind turbine subjected to "standard" ground motions.

5. CONCLUSION

This paper presents an overview of some of the important considerations for the reliable evaluation of the seismic risk to modern wind turbine support towers. These considerations include: (1) turbine-specific characterization of the susceptibility of the tower cross-section to local buckling, (2) site-specific assessment of both the strength and characteristics of ground motions, and (3) consideration of the response during the operational versus parked condition.

The paper also presents the results from a brief analytical study which showed that the spectral characteristics of the ground motion can have a significant impact on the fragility of a wind turbine. For this study, the fragility of one particular 80m, 2.4 MW wind turbine was shown to be the highest for soft soil ground motions and the lowest for firm soil ground motions with pulse-like ground motions having an intermediate fragility. Additionally, the analysis shows that the vulnerability is also dependent on the specific turbine design, even for turbines of similar height. More research work is required and some of it underway to more comprehensively address the seismic vulnerability of tubular wind turbine towers and wind farms, in general.

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