SHAKE TABLE TEST OF A 65kW WIND TURBINE AND COMPUTATIONAL SIMULATION

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ABSTRACT :

This paper presents the experimental results from an initial series of full scale shake table tests of a 65kW wind turbine with a 23 m hub height. Using the experimental results, a calibrated finite element model was developed to investigate and highlight salient characteristics of the wind turbine's seismic response. The model was subjected to a number of earthquake records from California. Five high-intensity historical input ground motions, which produced significant response in the turbine, were used to investigate the difference in seismic demand of a parked turbine for uni-axial and bi-directional excitation scenarios. The experimental data and simulation results shed light on the basic seismic response characteristics of wind turbines similar to that tested.

KEYWORDS: Renewable Energy, Seismic Design, Shake Table, Testing, Wind Turbine

1. INTRODUCTION

Installed wind power continues to grow rapidly worldwide, including North America and Asia. For instance, China has plans to deploy over 100 GW of wind power by the year 2020 (Pengfei, 2008), an amount approximately equal to the total current worldwide installed wind power (DOE, 2008). Both North America and Asia periodically experience strong earthquakes that may impact design loads for turbines. Therefore, appropriate consideration of seismic risk is becoming increasingly important with this growth of wind power in earthquake prone regions. Under-predicting this risk unduly exposes the operators and the communities dependent on wind power. Similarly, over-prediction of earthquake influence may lead to costly designs that undermine the economic feasibility of wind power. Thus, rational prediction of seismic considerations will maintain and enhance the ability of wind power to compete with other energy sources.

When selecting a new wind farm location, it is common practice to conduct a lengthy investigation to characterize the site specific wind conditions. Accepted methods exist for using this information to develop 50-year extreme wind condition predictions. These predictions are combined with extensive experimentation, practical experience, theoretical prediction, and numerical modeling to develop extreme design loads. In contrast, the process of estimating seismic forces on turbines is relatively new. Current practices for seismic loading vary greatly, but generally fall into one or both of two categories: numerical (finite element) analysis; and analysis based on building codes such as the 2006 International Building Code (ICC, 2006). It is widely recognized that the dynamic behavior of wind turbines is distinct from that of other building structures (Ritschel et al., 2003; Witcher, 2005). Of particular note is the requirement for wind turbines to behave elastically and sustain no damage during a 475 year return period earthquake (GL, 2003; IEC, 2005). From a performance-based design perspective it is also important to harmonize the different hazard scenarios for a holistic design of wind turbines.

In view of this challenge, research at the University of California, San Diego (UCSD) was initiated to experimentally investigate wind turbine earthquake response. The experimental setup for a full scale shake table test of a wind turbine is presented in this paper. Using results from this experiment, a finite element (FE) model was constructed and calibrated. A number of simulations were conducted using the model to determine earthquake records that resulted in high seismic demand. These records were further investigated (Prowell,

2010) in bi-directional shaking simulations using the developed FE model. On the basis of this initial study, some conclusions are drawn and directions for further investigations are discussed.

2. EXPERIMENT DESCRIPTION

To provide much needed data for validation of existing and future models of wind turbine behavior in response to earthquakes, a full scale test was conducted at UCSD. A 65 kW turbine, donated by Oak-Creek Energy Systems of Mojave, CA, was mounted on the Network for Earthquake Engineering Simulation (NEES) shake table located at UCSD and subjected to base shaking that simulated an actual earthquake. DC-coupled accelerometers attached to the turbine recorded the response of the tower. This data is of great value to assist in the development and calibration of methods for predicting forces experienced by a turbine during a seismic excitation event.

2.1 Physical Description of Test Turbine

The tested unit (Figure 1) is a Nordtank wind turbine manufactured in Denmark. A significant number of these turbines have been installed in California. They are characterized by high reliability and simple operation (Hau, 2006). This reliability and ease of operation has resulted in use beyond the design life, with retired units often being reconditioned and sold on the second-hand market. A 65 kW turbine represents the smallest size that would be considered for use in utility scale electrical power generation. In addition to being suitable for utility scale applications, this size unit is well suited for community power projects to augment or supply electricity for a small population. In comparison to modern turbines, the unit tested is small, but represents the most common turbine configuration, a thin walled tubular steel tower topped with a nacelle that yaws to orient the rotor into the wind. A summary of the engineering properties of the turbine is presented in Table 2.1.

Table 2.1: Wind Turbine Properties

Property	Value
Rated power	65 kW
Rated wind speed	33.8 km/H (21 MPH)
Rotor diameter	16.0 m (628 inches)
Tower height	21.9 m (864 inches)
Lower section length	7.9 m (313 inches)
Lower section diameter	2.0 m (80 inches)
Middle section length	7.9 m (312 inches)
Middle section diameter	1.6 m (62 inches)
Top section length	6.0 m (238 inches)
Top section diameter	1.1 m (42 inches)
Tower wall thickness	5.314 mm (0.2092 inches)
Rotor hub height	22.6 m (888 inches)
Tower mass	6400 kg (14.1 kips)
Nacelle mass	2400 kg (5.2 kips)
Rotor mass (with hub)	1900 kg (4.1 kips)

2.2 Shake Table Facility

The shake table tests were conducted on the UCSD, NEES Large High Performance Outdoor Shake Table (LHPOST). The LHPOST (Restrepo et al. 2005) was built to impart uni-axial excitation, with a platform of 7.6 m by 12.2 m in size, a stroke of ±0.75 m, a peak horizontal velocity of 1.8 m/s, a horizontal force capacity of 6.8 MN, an overturning moment capacity of 50 MN-m (for a 400 ton specimen), and a vertical peak payload capacity of 20 MN. The testing frequency range initially in the 0-20 Hz band was enhanced recently to 0-33 Hz band. As such, this table is the largest worldwide in terms of load capacity and the first outdoor facility of its kind. The facility adds a significant new capability to existing United States testing facilities with no overhead space and lifting constraints, which is essential for full scale wind turbine testing.

2.3 Experimental Test Program

In November 2004, the turbine described above was mounted on the NEES shake table and subjected to numerous base shaking events (with the rotor's axis of rotation perpendicular to the imparted motion). The turbine was parked such that the rotor had one blade oriented downward, parallel to the main tower for all test motions (Figure 1). To capture the lateral response, uni-axial accelerometers were installed on the turbine and table as indicated in Figure 2. One accelerometer was located on top of the shake table. Four others were located on the turbine tower, one at the base, one at the lower joint, one at the upper joint, and one on at the top of the nacelle.

Excitation used for the tests was derived from the East-West component (0.15 g peak ground acceleration) of the June 28th, 1992 strike-slip Landers Earthquake (moment magnitude M_w = 7.3) recorded at Desert Hot Springs (DHS). DHS is a California Strong Motion Instrumentation Program (CSMIP) station situated on deep alluvium located 23 km from the fault trace where the Landers Earthquake occurred. To remove any superfluous offset as well as high frequency noise, the earthquake record was filtered with a band pass of 0.05 Hz to 25 Hz. The record was scaled at 50%, 100%, 143%, and 200% of the original value for the shake table tests. As such, this was the first full scale base excitation test for a wind turbine.

Figure 1: Shake Table Setup

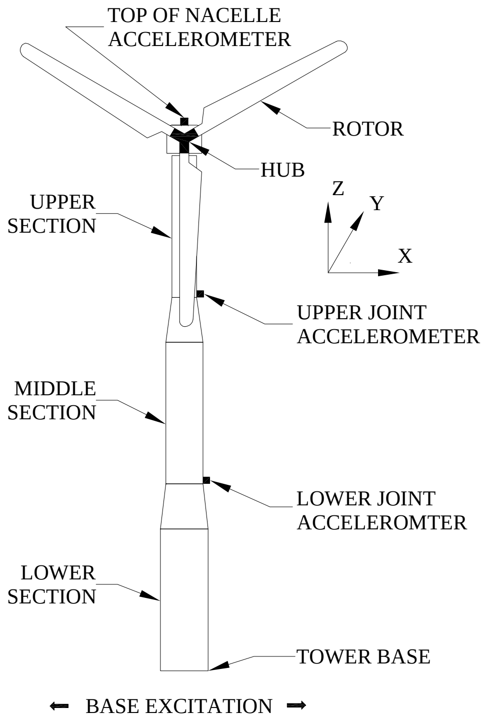

Figure 2: Accelerometer Locations

3. CALIBRADATED NUMERICAL MODEL

FE modeling is a common method for investigating response of civil structures to possible loading scenarios. As with all modern civil design, the wind industry actively uses this tool (Witcher, 2005; Haenler et al., 2006). Model parameters, such as damping, material properties, and boundary conditions strongly influence model results and are often difficult to ascertain. The validity and accuracy of FE results can be dramatically improved by using experimental results to calibrate a model and reduce parameter uncertainty. A calibrated model provides results with a higher degree of accuracy to loading scenarios that were not experimentally investigated.

Based on the engineering properties of the turbine (Table 2.1) a FE model was developed using OpenSees (Mazzoni et al., 2006). The tower and the three blades were represented by elastic beam-column elements with the flexural stiffness of the center of the section being modeled. The nacelle was modeled with rigid elements to connect the top of the tower to the rotor. Without calibration, the FE model accurately predicted the experimentally observed first natural frequency of 1.7 Hz within 0.5%. The first mode shape observed experimentally showed good agreement with that of the OpenSees model (Figure 3). This suggests that a relatively simple model is capable of adequately capturing the complexity of the dynamic behavior for the first mode. The experimental results did not indicate any modes in the direction of excitation between the primary mode and 10 Hz (Prowell, 2010). For the 65 kW unit discussed here, the first mode is the primary mode of interest for earthquake events, such as those recorded in California, without significant energy in the range of the observed higher modes. For larger turbines where higher modes occur at lower frequencies (Haenler et al., 2006) and regions where earthquake excitation may contain more high frequency energy, attention should be given to these higher modes.

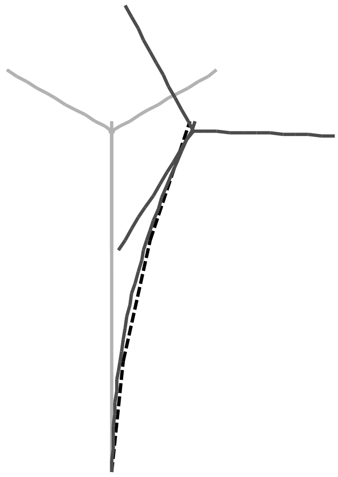

Figure 3: Observed (dashed) and Predicted (solid) 1st Mode Shape

Both the log decrement and half power methods (Chopra, 2001) were employed to asses the amount of viscous damping based on the experimental results. These methods resulted in damping values in the range of 0.4 to 0.6 % of critical damping. For this initial study, in view of the observed response and in agreement with industry guidelines (IEC, 2005), viscous damping was set to 1%. This damping is obviously much lower than the 5% that is typically used for simulating seismic response of civil structures (ICC, 2006). With this low damping, reasonably good agreement with the experimental results was achieved (Figure 4). As such, the FE model was deemed to be useful for drawing insight related to seismic response, by conducting numerical simulations.

4. NUMERICAL SIMULATIONS

The calibrated FE turbine model was used to conduct simulations of the response to a wide range of earthquakes recorded throughout California (Prowell, 2010). In light of certification guidelines for turbines, linear response was maintained without consideration of shell buckling and other non-linear phenomena. Such non-linear mechanisms must be carefully investigated upon exceeding of the linear capacity of the tower. This paper presents the results from a subset of the records investigated that were among those that generated significant amplification for the turbine studied (Table 4.1). Figure 5 shows the strong shaking portion of the 1981 Westmorland Earthquake acceleration time history recorded at the fire station in Westmorland, California.

The FE model described above was used to simulate the turbine's response to each of the recorded components from the records mentioned in Table 4.1. Uni-axial simulations were conducted for each earthquake component with the strong component of base excitation applied perpendicular to the rotor's axis of rotation (as imparted by the shake-table). Bi-directional simulations were conducted as well, with the weak component acting along the rotor's axis of rotation (Figure 2).

The resulting maximum moment predicted by the FE model at the base of the turbine for each simulation is presented in Table 4.2. It is noted that the moment produced by the Westmorland earthquake approaches the level allowed by the AISC (2005), when the tower was idealized as a slender tube (Prowell, 2010). Fortunately, all other motions (Table 4.2) resulted in moments that were below this threshold. For considering tower capacity where an entry door or other similar cut-out may be present, special attention beyond the employed simple idealization must be exercised (Bazeos et. al, 2002).

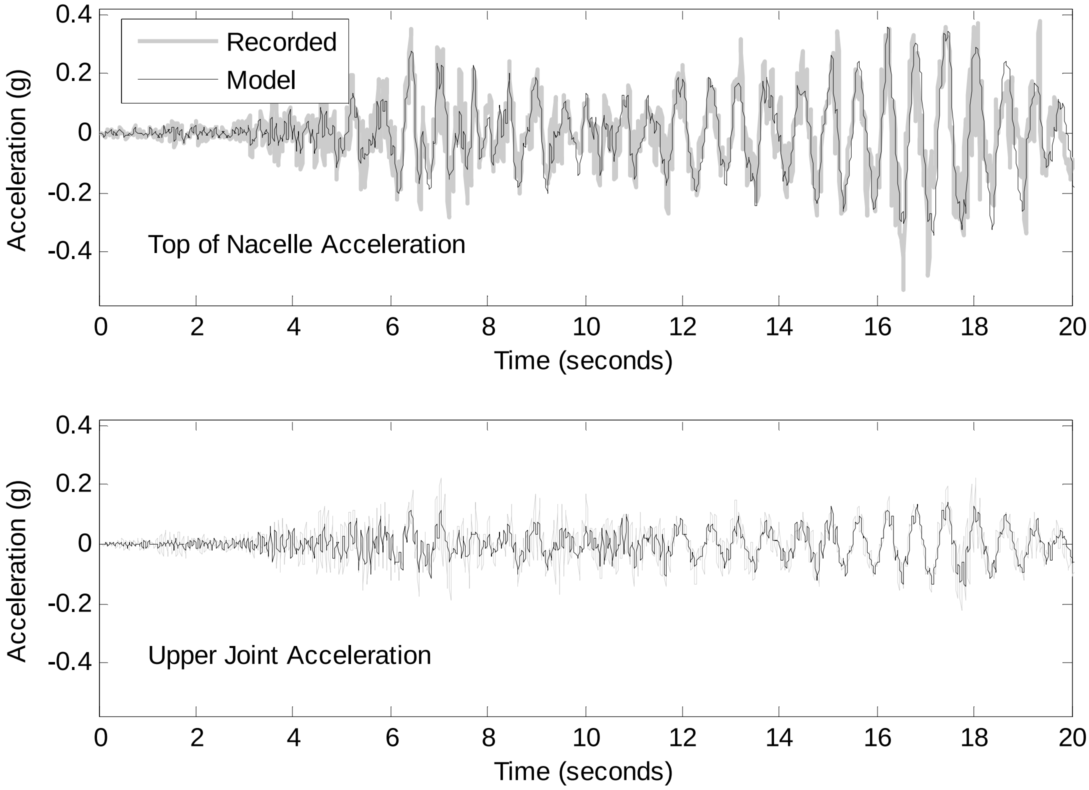

Figure 4: Recorded and Simulated Results for 143% Test

Table 4.1: Summary of Earthquakes

Earthquake	Moment Magnitude	Station	PGA	Source Distance
1981 Westmorland	5.9 M_w	Fire Station	0.50 g	7.2 km
2000 Yountville	5.0 M_w	Fire Station No. 3	0.41 g	13.7 km
1986 Palm Springs	6.2 M_w	New Fire Station	0.33 g	6.8 km
1940 El Centro	6.9 M_w	Array Station 9	0.35 g	12.2 km
1979 Coyote Lake	5.7 M_w	Gilroy Array Station 6	0.42 g	13.6 km

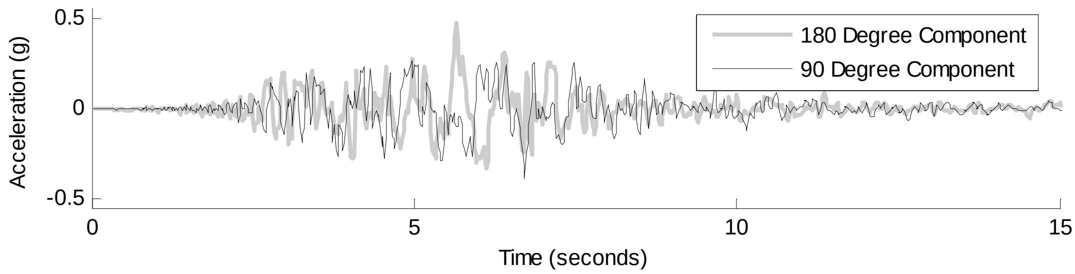

Figure 5: 1981 Westmorland Earthquake Acceleration Time History Recorded at Fire Station

The response (Figure 6) to the 180 degree component of the 1981 Westmorland Earthquake recording (Figure 5) clearly displays dominance of the first mode response. In view of the mild eccentricity contained in the current model configuration, little coupling occurs between the two horizontal shaking directions, where minimal difference between the uni-axial and bi-directional simulations may be noted in the direction of dominant response (Figures 6 and 7).

Table 4.2: Summary of Simulated Results

Simulation	Weak Component	Strong Component	Bidirectional	Bidirectional Increase
1981 Westmorland Fire Station	1,010 kN m	2,603 kN m	2,657 kN m	2%
2000 Yountville Fire Station No. 3	1,254 kN m	1,681 kN m	1,735 kN m	3%
1986 Palm Springs New Fire Station	538 kN m	1,478 kN m	1,478 kN m	0%
1940 El Centro Array Station 9	1,161 kN m	1,437 kN m	1,641 kN m	14%
1979 Coyote Lake Gilroy Array Station 9	504 kN m	1,165 kN m	1,180 kN m	1%

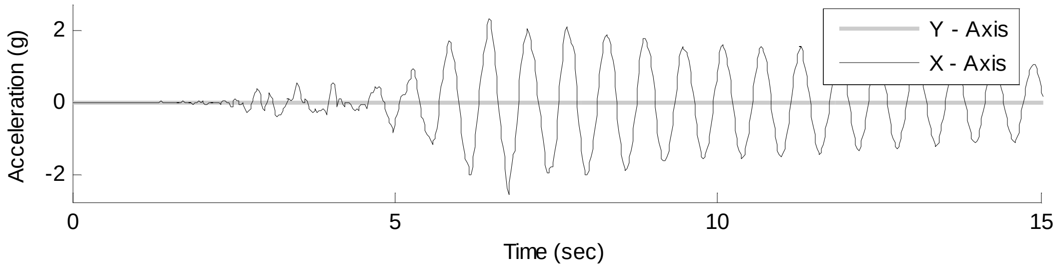

Figure 6: Acceleration Response at Top of Turbine for Strong Component Westmorland Earthquake Simulation

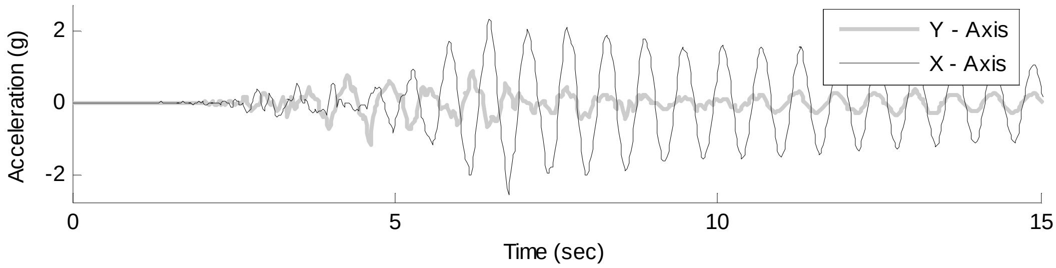

Figure 7: Acceleration Response at Top of Turbine for Bi-directional Westmorland Earthquake Simulation

The moment demand for bi-directional loading shows minimal increase for most of the records in Table 4.2. El Centro, was the only record that resulted in a significant increase of about 15%. The other records showed a low weak-direction response, and/or an out of phase response for the two axes. Based on this initial simple analysis, the effects of bi-directional loading fell below code recommendations. For instance, the IBC 2006 suggestion (ICC, 2006) of 100% and 30% of the moment from independent uni-axial simulations would be on the conservative side. Further studies are warranted to further explore this issue.

5. CONCLUSION

This paper presented results from the first full scale shake table test of a wind turbine. The experiment was instrumental in demonstrating the feasibility of full scale testing for such structures, which today approach heights in excess of 80 m. Findings from the experiment show that: i) for the investigated relatively small 23 m turbine, the first mode dominated the seismic response for the investigated motions, with higher modes potentially participating for high frequency seismic input situations (10 Hz and more), and ii) at the fundamental mode, the viscous damping ratio may be as low as 0.5%. The recorded preliminary results also provided a basis for verification and calibration of a simple FE model. Using this model, some insights were gleaned from seismic shaking simulations, where: i) tower moments were mostly within the capacity of an idealized slender tube (not withstanding possible reductions due to presence of doors and similar cut-outs), and ii) Code based recommendations for addressing the impact of bi-directional loading may be conservative and warrant further investigation for design driving situations.

The experimental results presented herein provide valuable information, and serve as a first step in the validation of seismic behavior of wind turbines. The reported research is currently continuing with the assistance of NEES facilities through: i) in-situ vibration measurements of parked and operating turbines for seismic demand and soil-structure interaction evaluations, ii) additional full scale experiments and associated modeling with the aim of assessing nonlinear response and the tower moment capacity. The outcome of these experiments and modeling effort, will be a performance-based probabilistic seismic risk analysis framework, comprehensively addressing the underlying load scenario combinations (GL, 2003; ICC, 2005).

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