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SEISMIC RESPONSE OF A 5-MW WIND TURBINE: THE SHAKEOUT SCENARIO

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ABSTRACT

In November 2008, the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) sponsored "The Great Southern California ShakeOut" to raise awareness about the possible ramifications of a 7.8-magnitude earthquake along the San Andreas Fault. Such an earthquake would directly affect Palm Springs, California, a prime location for wind power. California's Assembly Bill (AB) 32 (2006), legislation requiring reduction in emissions to 1990 levels by 2020, reinforces the importance of investigating the influence that seismic events might have on design loads for new large wind turbines. Anticipating that turbines will grow larger than the current 3-MW models with a hub height of 80 m, we examined the ramifications of a motion derived for The Great Southern California ShakeOut on the National Renewable Energy Laboratory's (NREL) 5-MW baseline wind turbine model with a hub height of 90 m. The resulting structural demand is compared for scenarios where the turbine is idling, continues operation, and initiates an emergency shutdown.

Introduction

Since utility scale wind power was introduced in the U.S. in the 1980s (Hau 2006), the amount of electricity produced from the wind has grown steadily (Wiser and Bolinger 2009). With the passage of Assembly Bill (AB) 32 (2006), wind power is poised to expand in California. Early turbines used many design variations, but the market has stabilized on the three-bladed upwind variable-pitch turbine (Fig. 1) for commercial wind farms (Hau 2006). Each generation of turbine has increased in size from early commercial turbines with an 18-m rotor diameter to current turbines with rotors exceeding 100 m in diameter (Malcolm and Hansen 2006).

Of the loading sources considered for wind turbines, earthquakes receive relatively little attention (Prowell and Veers 2009), but are still included by regulating bodies for regions such as California (GL 2003; IEC 2005). Despite nonlinear interaction between seismic and wind loads, they are often considered by superimposing independent simulations. Early investigations (Bazeos et al. 2002; Lavassas et al. 2003) mirror this approach by focusing on tower loading

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using models that lump the nacelle and rotor as a point mass (Fig. 1) when determining the seismic component of the response.

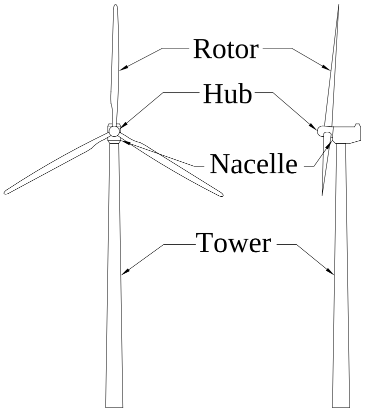


Figure 1. Wind turbine configuration

As turbines grew larger and more expensive (Wiser and Bolinger 2009), new technologies such as variable pitch and active control sometimes changed the design-driving considerations, with fatigue and turbulence becoming important considerations along with extreme events (Malcolm and Hansen 2006). Through these active control techniques and intelligent design, modern turbines can be optimized to be lighter and more cost effective. For these lighter turbines, simulating earthquake and wind loads simultaneously in the time domain becomes desirable to reduce the uncertainty of the results.

This goal is apparent in the shift of simulation efforts to more refined approaches that consider wind and seismic loads simultaneously (Ritschel et al. 2003; Witcher 2005; Haenler, Ritschel, and Warnke 2006; Zhao and Maisser 2006). The standard load case of an emergency shutdown triggered by an earthquake (IEC 2005) also motivates migration to models that include dynamics of the rotor (Fig. 1). We used recent modifications (Prowell, Elgamal, and Jonkman 2009) to the FAST code (open-source software capable of modeling turbine dynamics, Jonkman and Buhl 2005) to conduct time-domain simulations that assess the implications of a strong earthquake on the structural demand of the National Renewable Energy Laboratory's (NREL) 5-MW baseline wind turbine (Jonkman et al. 2009).

Palm Springs was selected for the hypothetical turbine location because it is a prime site for wind energy (Hau 2006). In addition, its proximity to the San Andreas Fault, which traverses much of California and is capable of producing significant earthquakes, leaves Palm Springs highly vulnerable to seismic hazard. On November 13, 2008, many corporations, government agencies, and private individuals participated in "The Great Southern California ShakeOut" to raise public awareness about and promote readiness for a possible 7.8-magnitude earthquake (Jones et al. 2008). As part of this exercise, a plausible set of ground motions was developed for areas throughout Southern California, including Palm Springs (Bielak et al. 2010). In this paper, we compare a simple analysis based on the 2006 International Building Code (2006 IBC, ICC 2006) and the International Electrotechnical Commission Guidelines (IEC 2005) with a time-domain simulation of a Southern California shakeout motion for the site.

Turbine Description and FAST Model

Researchers at NREL's National Wind Technology Center (NWTC) have developed a reference 5-MW turbine to serve as a standard model for conceptual studies of modern multimegawatt turbines. The FAST model of the 5-MW turbine we used here matches that presented by (Jonkman et al. 2009). Table 1 gives pertinent structural details. As Haenler, Ritschel, and Warnke (2006) noted for another large turbine with an 80-m rotor diameter, many natural frequencies for the 5-MW reference turbine occur within the range of interest for earthquake loading and may be excited during an earthquake (Table 2).

Table 1. Main parameters of reference wind turbine

Type	**Horizontal wind turbine**
Power rating	5 MW
Rotor configuration	3-blade upwind
Control	Variable-speed, collective-pitch
Drivetrain	High-speed, multiple-stage gearbox
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Rotor speed range	6.9 to 12.1 rpm
Rotor diameter	126 m
Hub height	90 m
Tower height	87.6 m
Mass of rotor	110,000 kg
Mass of nacelle	240,000 kg
Mass of tower	347,460 kg

Source: Jonkman et al. (2009)

Table 2. Fixed-base natural frequencies of the parked wind turbine

Mode description	**Frequency (Hz)**
1st tower fore-aft	0.32
1st tower side-to-side	0.31
1st blade asymmetric flapwise yaw	0.67
1st blade asymmetric flapwise pitch	0.67
1st blade collective flap	0.70
1st blade asymmetric edgewise pitch	1.08
1st blade asymmetric edgewise yaw	1.09
2nd blade asymmetric flapwise yaw	1.93
2nd blade asymmetric flapwise pitch	1.92
2nd collective flap	2.02
2nd tower fore-aft	2.90
2nd tower side-to-side	2.93

Source: Jonkman et al. (2009)

Site Characteristics and Seismic Design Loads by Simple Analysis

The site considered near Palm Springs is located at latitude 33.83070° and longitude 116.51840°. Because the mountains to the north and south concentrate the air currents coming across the Los Angeles basin, the site is well suited for producing energy from the wind. The topography that funnels the wind was shaped by the San Andreas Fault.

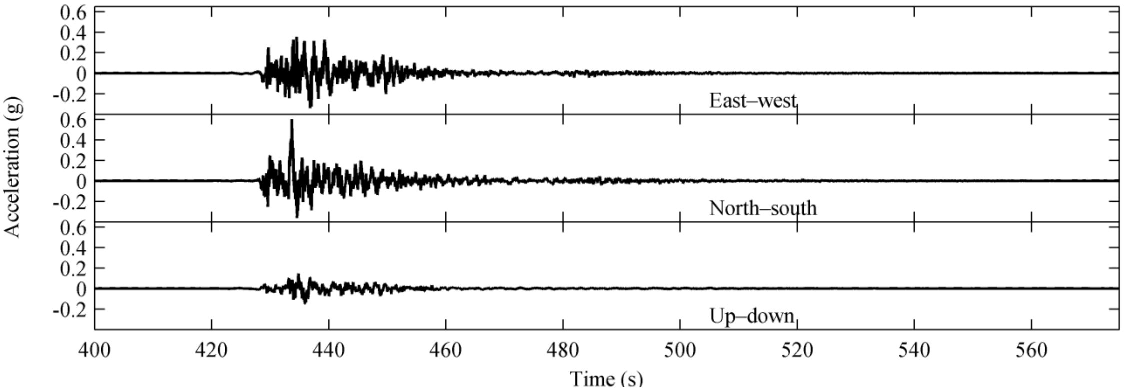
IEC guidelines (IEC 2005) allow the use of a simplified analysis to develop seismic design loads for the turbine tower. This procedure defers to local code, and California follows the 2006 International Building Code (IBC, ICC 2006) to define seismic hazard. Assuming a rock site, Site Class A, with an R factor of 1—(elastic response is required for turbines, IEC 2005)—the 2006 IBC results in a design acceleration of 0.1 g for a structure with a period of 3.2 s (F = 0.31 Hz). For locations such as the selected site, where the spectral response acceleration at a period of 1 s (S_1) is equal to or greater than 0.6 g, the minimum base shear is limited by Eq. 12.8-6 from the 2006 IBC (ICC 2006, p. 129), which limits the design acceleration for the Palm Springs site to 0.3 g. As Agbayani (2002) observed, these code provisions for minimum base shear can govern the simplified seismic design acceleration for large turbines. Per IEC guidelines, the design acceleration should be modified from the assumed damping, which is 5% in the 2006 IBC, to a 1% damped level, which can be calculated through the simple procedure outlined by Naeim and Kircher (2001). Because the resulting 1% design acceleration of 0.13 g is less than the code minimum of 0.3 g, we used the code minimum value. In accordance with simplified industry guidelines (IEC 2005), the seismic base moment can be found by Eq. 1 where the IEC point mass is defined as the nacelle and rotor mass plus half of the tower mass.

$$\text{Tower Base Moment} = (\text{IEC point mass})(\text{design acceleration})(\text{tower height}) \tag{1}$$

For the design acceleration of 0.3 g, a tower height of 87.6 m, and a mass of 523,730 kg the base moment is 135 MN-m. Once the seismic base moment is defined, it must be added to the characteristic loads for an emergency shutdown. Such an analysis is beyond the scope of this paper, so we considered instead a published value of 98 MN-m for the extreme fore-aft tower base moment at a wind speed near 15 m/s (Fogle, Agarwal, and Manuel 2008). In another study, Jonkman (2007) observed a maximum moment of approximately 85 MN-m. Using a load factor of 1.25 for normal operation and 1.2 for extrapolation to extreme loads, resulting in a total factor of 1.5, a range of 128 MN-m to 147 MN-m is required of the tower (IEC 2005). For extreme turbulence simulations with a load factor of 1.35 (IEC 2005), Jonkman (2007) found that the maximum moment demand was 153 MN-m. Our time-domain simulations (described later in this paper) show that an emergency shutdown during an earthquake actually leads to lower design loads than continued operation. Superimposing these demands from the wind loads with the simplified seismic assessment results in total design base moments ranging from 263 to 288 MN-m for the 5-MW reference turbine when located at the proposed site.

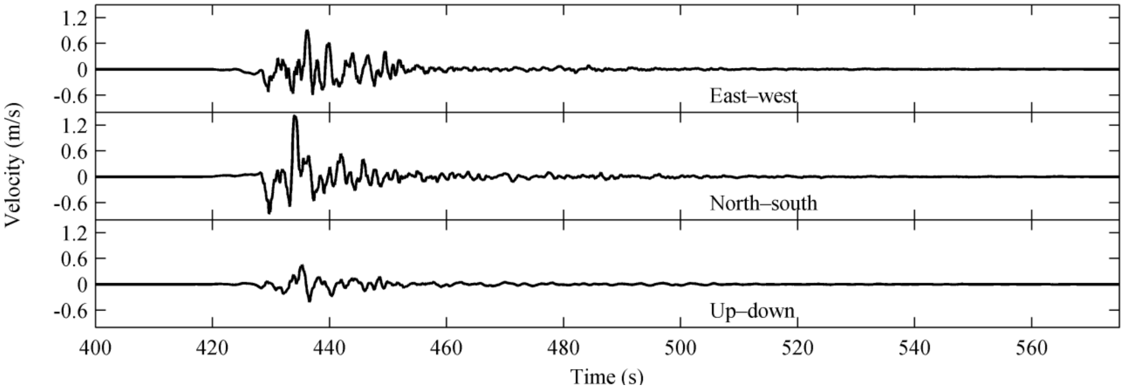
Simulation of Combined Seismic and Wind Loads

We used the FAST turbine model to conduct base-shaking simulations for a simulated motion from the Southern California shakeout (Bielak et al. 2010) for three scenarios: idling, continuous operation through the earthquake, and emergency shutdown. The southern San Andreas Fault has, on average, produced an earthquake of similar magnitude to the shakeout motion every 150 years (Bielak et al. 2010). As a result, the motion is more probable than that considered by the 2006 IBC analysis, which assumes a 2,500-year return period (ICC 2006). The simulated acceleration, velocity, and displacement for the Southern California shakeout are shown in Figs. 2, 3, and 4, respectively, with the time scale shifted to match the delay used in the simulations. The motion contains a peak ground acceleration of 0.62 g in the north–south direction. The axis of rotation for the rotor (Fig. 1), X direction, is aligned with the north–south motion; the east–west excitation is applied in the Y direction, perpendicular to the axis of rotation for the rotor. We used both horizontal components and one vertical component of the record, and conducted the simulation assuming a fixed-base condition, which is suitable for the stiff soils found at many wind farms. Further consideration of soil structure interaction would be warranted for locations with soft soils (Bazeos et al. 2002; Zhao and Maisser 2006; Prowell, Elgamal, and Lu 2010).



Source: Bielak et al. (2010)

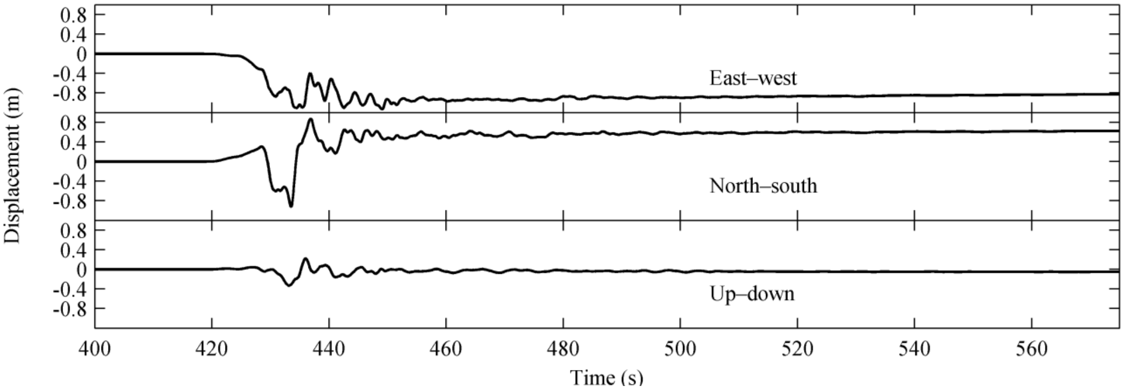
Figure 2. Shakeout ground acceleration near Palm Springs, California



Source: Bielak et al. (2010)

Figure 3. Shakeout ground velocity near Palm Springs, California

For the idling simulation the blades are fully feathered. Both operational simulations use the baseline generator-torque and blade-pitch controller of the NREL 5-MW turbine to control the turbine behavior. The emergency shutdown scenario is initiated 3 s after the earthquake shaking starts, shortly after the onset of earthquake-induced strong nacelle vibration. To accomplish the shutdown, full feathering of the blades is initiated at the maximum pitch rate for the NREL 5-MW turbine, 8.0 °/s. For all simulations we used a stochastic wind field with a mean velocity of 11.4 m/s in the X direction (aligned with the drive shaft). An initial period of 400 s was simulated to allow initial transients to diminish before the earthquake shaking started.



Source: Bielak et al. (2010)

Figure 4. Shakeout ground displacement near Palm Springs, California

Figs. 5 and 6 compare the resulting acceleration of the nacelle for each simulation. The X direction (north–south) response (Fig. 5) is governed by the acceleration pulse just before second 434 in the simulation. The dissipation of the vibration caused by this pulse is then dependent on the orientation of the blades, with the running simulation showing the most aerodynamic damping. In contrast, the Y direction (east–west) response (Fig. 6) gradually builds from 440 to 450 s, driven by the continued strong shaking in the input. In the shutdown scenario, the rotor was nearly stopped by this point, leading to the observed similarity to the idling case. Of interest to note is that the emergency shutdown damps out the motion more rapidly in both directions because the feathering of the blades creates aerodynamic damping, first in the X direction and then in the Y direction. It could be advantageous to capitalize on the large influence of aerodynamic damping from the blades by unfeathering the blades or by initiating yawing of the turbine to diminish the prolonged shaking observed from the earthquake excitation.

FAST uses modal superposition based on four tower modes (two in each horizontal direction) and three blade modes (two flap and one edge) to model the turbine tower and blades (Jonkman and Buhl 2005). This works well for situations where excitation comes from the wind and operational vibrations while ensuring rapid simulations for statistical analysis of loads (e.g. Fogle, Agarwal, and Manuel 2008). For the 5-MW reference turbine, such a model only considers modes up to 2.93 Hz (Table 2), but earthquake excitation often contains energy well above this level. To verify the results presented here, a finite element model of the 5-MW reference turbine (Prowell, Elgamal, and Lu 2010) was subjected to the same ground acceleration (Fig. 2). The finite element model was developed using OpenSees (Mazzoni, McKenna, and Fenves 2006) and is capable of simulating higher modes. Only the parked trial, without wind loading, was simulated because OpenSees is not capable of properly modeling the operational or aeroelastic dynamics. The results (not shown here) agree with those presented for the FAST simulations (Figs. 5 and 6), but show slightly lower structural demand because wind loads are not considered. This improves confidence in the FAST code simulations.

To investigate the possible implications of the three scenarios on design loads, we calculated the maximum moment demand at the base, at four locations along the tower, and at the top of the tower (Fig. 7). This maximum is taken from the square root of the sum of the squares (SRSS) of the two horizontal tower moments at each time step. Fig. 7 shows the resulting demand for each of the three scenarios. The time-domain simulation for idling and running cases exceeds the demand from the simplified analysis presented earlier. These results clearly illustrate the advantage of being able to consider earthquake and wind loading simultaneously. Of the three scenarios, the idling simulation results in the highest demand. In the emergency shutdown case, despite the added demand from the wind, aerodynamic damping contributes to the overall structural damping and results in a lower total moment demand in the tower.

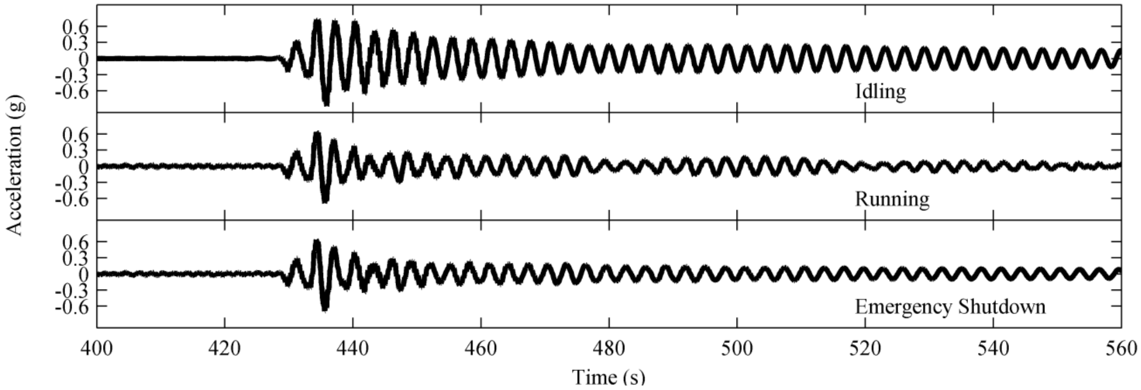


Figure 5. Nacelle acceleration in X direction (fore-aft)

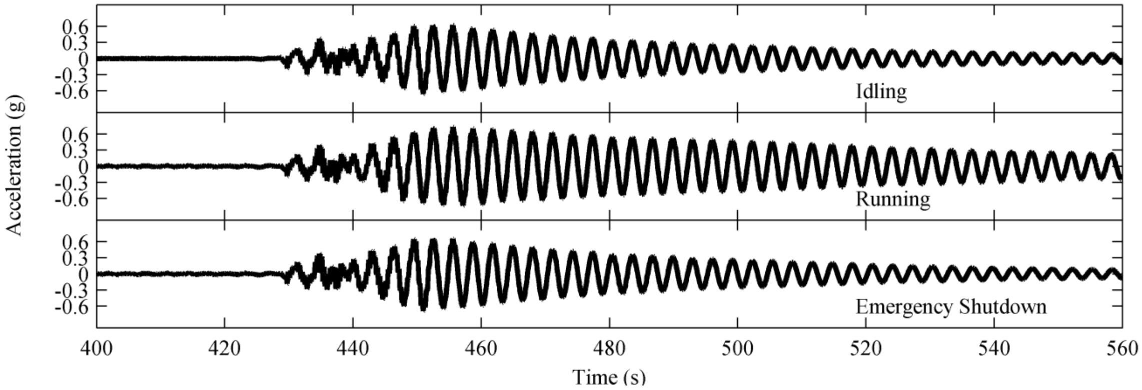


Figure 6. Nacelle acceleration in Y direction (side-side)

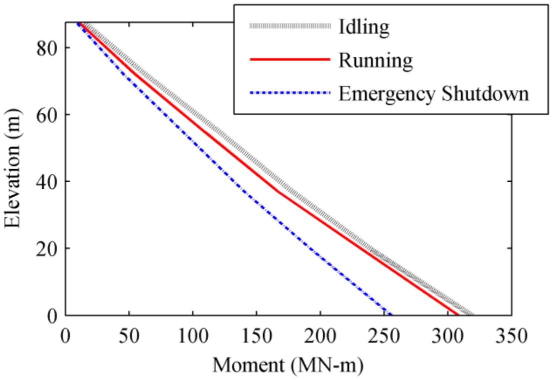


Figure 7. Tower moment demand

In addition to tower moment demand, which is frequently assessed using a simple model of a turbine (Bazeos et al. 2002; Lavassas et al. 2003), conducting the simulation with the FAST code allows the designer to understand the seismic influence on the blades and other components. To illustrate this ability, the blade to tower clearance is shown in Fig. 8. For the idling case, and for the latter portion of the shutdown case, the rotor was oriented such that the clear distance between the tower and blades exceeded the full scale of Fig. 8. This plot shows that the earthquake excitation has almost no influence on the clearance. Such behavior is expected because the earthquake motion must be transmitted through the tower, which has been designed to ensure that the natural frequencies do not coincide with the blade natural frequencies (Table 2) or with harmonics of the rotor revolution. Understanding this and other component demand parameters may be critical to properly addressing the influence that earthquakes exert on the turbine.

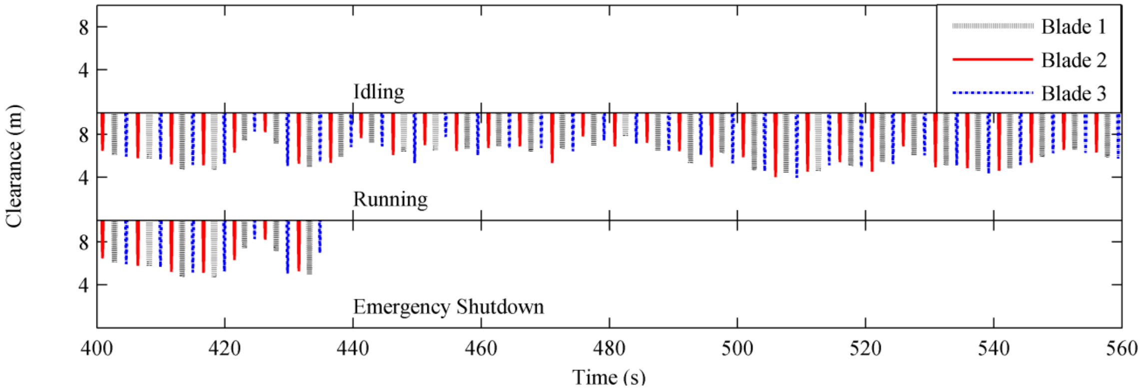


Figure 8. Blade to tower clearance

Conclusion

This paper presents two methods of analysis to derive seismic design base moments for the tower of a 5-MW turbine: a code-based approach and a numerical simulation using what is reported to be a plausible earthquake for the site considered. Both methods produced results exceeding what might be anticipated from operational wind loads. The IEC simplified approach (IEC 2005), which is reported to be conservative, also produced loads lower than the FAST simulation. Given that many design considerations exist for turbines (Lavassas et al. 2003; Jonkman et al. 2009) the reported differences might not alter the turbine design. Similarly, an in-depth benefit analysis might show that the risk of damage or even collapse from such a significant event is more appropriately dealt with through other means such as additional insurance instead of design modifications. The added seismic loading to FAST now allows designers to readily consider site-specific risk analysis by allowing a suite of ground motions, wind conditions, and control system variations to be considered with other pertinent turbine dynamics directly in the time domain. As shown, these simulations allow the consideration of the influence on components beyond just the turbine tower.

At the University of California, San Diego (UCSD), as part of this effort, full-scale experiments are being conducted to inform and refine modeling of wind turbines for earthquake-induced loads (see, for example, Prowell, Elgamal, and Jonkman 2009; Prowell et al. 2009; Prowell et al. 2010). Feedback from findings will be used to refine the capability of the FAST code to accurately incorporate base shaking as a load source for wind turbines. If needed to produce accurate results, additional modifications to FAST will be considered to simulate more structural modes. Accurate modeling will ensure wind turbines are a competitive component of renewable energy resources required to realize the goals of California AB 32.

Acknowledgments

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