Probabilistic Combination of Earthquake and Operational Loads for Wind Turbines

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SUMMARY:

This paper provides a probabilistic basis for appropriate resistance and partial load factors to facilitate design and installation of resilient wind turbines in seismically active regions. This study subjects a 5-MW wind turbine model to stochastic wind loads and historical records of earthquake motions, and simulates dynamic structural responses using the National Renewable Energy Laboratory (NREL) FAST code. The simulation takes into account the aeroelastic behaviour of the turbine. The research develops structural demand models and employs probabilistic load modelling and modern reliability-based load combination techniques to assess load combination requirements involving operational and earthquake loads. The study compares different load combination alternatives for meeting different performance objectives. With the target annual reliability index $\beta = 2.5$ with a 0.6% failure probability, the investigation observes that partial load factors of 1.1 and 1.4 should be applied to computed mean operational and seismic loads, respectively, when combining these loads for a running wind turbine. Furthermore, the nominal strength of the tower should be reduced by a resistance factor of 0.7. As presented, the load factors are not directly applicable to seismic load effects computed based on design values from current codes of practice. However, the analysis and reliability-based approach offer a rational basis to improve future load combination criteria in provisions for wind turbine design.

Keywords: Wind turbines, seismic load, load combination, reliability, limit state design

1. INTRODUCTION

Wind power continues to be the fastest growing renewable energy resource throughout the world. In the United States (US), wind energy capacity reached almost 50 GW by the end of 2011 (AWEA, 2012), and it had been the second-largest new resource added to the national electrical grid, behind natural gas plants for the fifth conservative year as of 2009 (Wiser and Bolinger, 2010). It currently accounts for about 3% of the electricity generated within the U.S. The growth has been facilitated by developments of new wind turbines with large configurations (rotors now exceeding 100 m in diameter). This rapid growth also includes significant expansions of the resource in earthquake-prone regions. This is clearly evident with nearly 1 GW added in California alone during 2011, resulting in a total capacity of almost 4 GW in a region known for frequent earthquakes.

Until recently, seismic loads had received less attention as compared to other load sources for wind turbines. Little guidance was available for consideration of an earthquake striking a turbine and analysis methods were adapted from conventional civil structures. This practice resulted in seismic loads being considered independently from other load cases in seismically active regions, such as California. However, as turbines were placed in areas known to have significant both seismic hazard and consistent winds, permitting agencies started to request consideration of a load case that included both operational and earthquake loads. Designers would frequently add results of two independent analyses because of the lack of appropriate tools or published guidance. This procedure is undesirable because it does not capture the interaction between load sources and may, in terms of reliability, produce inconsistent and overly conservative results.

The current International Electrotechnical Commission standard (IEC 61400-1) (2005-08) provides a simplified method for estimating the combined operational and seismic demands on a wind turbine by simply adding the estimated seismic load, which are factored from codes to the operational loads from independent analyses. Beyond this suggestion for combining loads, little guidance exists documenting best practices. As such, structural designers tend to rely on existing codified criteria developed for buildings and other structures. These codified criteria do not account for the particulars of wind plants, such as the aeroelastic behaviour of turbines under wind loads. Furthermore, the American Wind Energy Association (AWEA) in a joint effort with the American Society of Civil Engineers (ASCE) has developed a recommended practice (AWEA/ASCE, 2011) for the design of wind turbine support structures to facilitate permitting process. The document recommends that a 0.75 load factor be applied to combine peak seismic and operational loads, which are independently computed. This provision is based on research by Prowell (2011), which subjected a wind turbine model to simultaneous loading of wind (with a single wind speed) and earthquake motions. As such, the provision, although practical, can benefit from a probabilistic basis, on which load combinations are evaluated by exploring wide ranges of wind speeds simultaneously with earthquake intensities, and explicitly integrating uncertainty inherent in the structure and loading via reliability theory.

The current study explores practical probability-based load and resistance factors for wind turbine towers. The study employs the FAST code which is an aeroelastic simulator to generate dynamic structural responses of a modern wind turbine under simultaneous wind and earthquake excitations, and embeds it into a probabilistic model to account for inherent loading and system uncertainty. Simulated responses are used to develop structural demands for three operating scenarios – running, idling and earthquake-induced shutdown. The demand models and existing structural capacity models coupled with annual probability distributions of loads are used to derive partial load factors on the basis of first order second moment (FOSM) theory and the first order reliability method (FORM) (Rackwitz and Flessler, 1978, Ellingwood and Galambos, 1982). Thus, this study provides a methodological foundation to assess partial load factors for wind turbine load combinations, but such a methodology is not directly compatible yet with load provisions in existing designs standards. Compatibility will be determined for the design of wind turbine towers in on-going investigations.

The paper is divided into six sections. The next section describes the framework for numerically simulating structural responses of a wind turbine under operational load and earthquake excitations. Section 3 presents demand models approximated from simulated responses using regression methods. Reliability tools required to evaluate load combinations are explained in the fourth section. This section also provides probabilistic models for tower capacity, seismic, and operational loads. Section 5 discusses the partial load factors derived using the identified demand models, reliability tools, and probability models of previous sections. A summary of the study and key conclusions as well as future research efforts are contained in the final section.

2. NUMERICAL SIMULATIONS

The FAST code (Jonkman and Buhl Jr. 2005) was selected for response simulations due to its ability to consider all pertinent dynamics of a modern turbine subjected to earthquake shaking (Prowell, et al. 2010).

2.1. Wind turbine model

The study utilizes the 5-MW reference wind turbine model developed by the National Renewable Energy laboratory (NREL) (Jonkman et al., 2009) for utility-scale turbine studies. Pertinent parameters of the turbine are documented in Table 2.1. The used configuration, a 3 bladed upwind variable pitch horizontal axis wind turbine, is typical of modern turbines deployed and in development through the world.

Table 2.1. Main parameters of the 5-MW wind turbine under investigation

Type	Horizontal wind turbine
Power rating	5-MW
Rotor Configuration	3 blade upwind
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple-stage gearbox
Hub Height	90 m
Cut-in Wind Speed	3 m/s
Rated Wind Speed	11.4 m/s
Cut-out Wind Speed	25 m/s
Rotor Speed Range	6.9 to 12.1 RPM
Rated Tip Speed	80 m/s
Rotor diameter	126 m
Tower height	87.6 m
Mass of rotor	111,000 kg
Mass of nacelle	240,000 kg
Mass of tower	347,460 kg

2.2. External loads

Previous work illustrates that due to the low probability of simultaneous large earthquakes along with extreme wind conditions, it is overly conservative to consider extrema in an additive fashion for both wind and earthquake induced loads (Kiyomiya, et al. 2002). In fact, for large modern variable pitch turbines it is common for relative maxima in tower bending moments to occur around the rated wind speed of the turbine, which is an operational state that will likely occur during an extreme earthquake (Fogle, et al. 2008). Turbine certification guidelines require consideration of this load case where the turbine is subjected to normal operating conditions along with a scenario where an emergency shutdown is initiated by the earthquake (IEC 2005). The study presented here aims to understand the interplay of these loads and determine appropriate demand models across a wide range of plausible loading conditions.

For the development of a desired robust demand model that accounts for the turbine response across a range of wind conditions, the TurbSim program was used to generate 100 stochastic wind fields (Jonkman 2009). The generated wind fields range in hub-height wind speed from near the turbine cut-in speed to 20 m/s. Half of the generated wind fields contained an IEC turbulence level of A (I_{ref} = 0.16) and remaining contained a turbulence level of B (I_{ref} = 0.14) to explore the influence of wind turbulence. Due to past observations that significant wind demand occurs near operational wind conditions, a Weibull distribution (Eq. 2. 1, λ = 11.4 and k = 3.5) was selected to determine bin spacing for wind speeds.

$$\mathrm{f}(x,\lambda,k)=\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}} \tag{2.1}$$

Ground motions were selected from a vetted collection of 99 earthquakes spanning small magnitude distant events to large magnitude near field events (Mackie and Stojadinovic, 2005). Based on past efforts to evaluate efficient and robust intensity measures for wind turbines, the square root of the sum of squares (SRSS) of pseudo spectral acceleration (PSA) for each of the horizontal earthquake components is used (Prowell, 2011). At the first period of the studied turbine, the motion set contains records with PSA ranging from to near 0.1 m/s^2 to approximately 5 m/s^2.

Using a systematic experimental design, a set of 150 simulations was determined to generate various combinations of wind speed, wind turbulence, and earthquake excitation. Parameters were selected such that the considered probability distribution for wind speed (Eq. 2.2.1) was maintained. For both the turbulence levels, and the SRSS PSA realizations were distributed uniformly. The resulting set includes frequently occurring scenarios which are unlikely to cause extreme loads as well as those which are highly unlikely, but may result in extreme structural demand. This approach provided a results set which informs demand prediction across a wide range of plausible scenarios while simultaneously reducing the computational effort that would be required to run all combinations of considered external loading. Figure 1 graphically illustrates the combinations of PSA and wind speed that were considered.

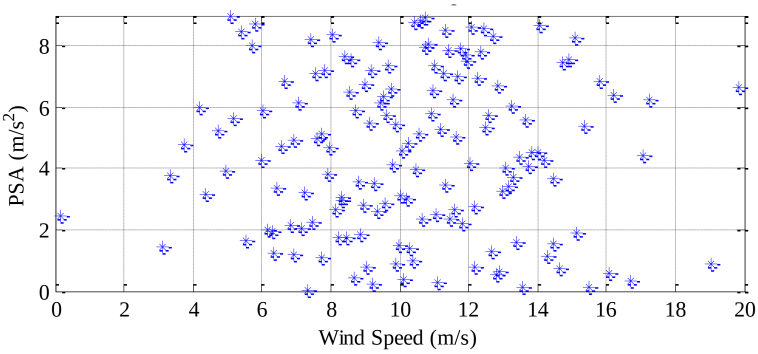


Figure 1. Combinations of wind speed and PSA considered

2.3. Response simulations

After the completion of the experimental design, simulations were executed in FAST for three operational scenarios where the turbine was subjected to the pre-determined combinations of wind speed, turbulence, and earthquake shaking. In the first scenario, normal operation for power generation is modelled. In this condition, active pitch control is engaged using the provided controller logic. For the second scenario, the turbine was idling with the blades fully pitched to prevent the generation of torque from the wind. In this idling scenario, the high speed shaft brake is not engaged, thus representing the expected state of the 5-MW machine while not producing power. The final scenario, an emergency shutdown initiated by excess acceleration in the nacelle, mimicked the operational scenario whit the occurrence of earthquakes. A fault acceleration of 1 m/s^2 was used to trigger initiation of blade pitching to shut down the turbine. All three blades were collectively pitched at the maximum rate of eight degrees per second for the studied turbine. For simulations where an acceleration of 1 m/s^2 was not exceeded, regular operation continued, resulting in no difference between the operational and emergency shutdown scenarios. This situation was somewhat common for low PSA values, but not for the scenarios with strong earthquake motions.

A total time of 600 seconds at a time step of 0.001 seconds was considered for each simulation. For the first 400 seconds, wind and operational loads were the sole source of loading in all simulations to allow initial transients to diminish. Following this time period, earthquake shaking was applied. To reduce the likelihood of bias due to the relative orientation of wind and earthquake shaking, the simulation set was run twice, with the horizontal motion components interchanged, for each external load combination and operational scenario. In addition to the seismic simulations, a set of simulations were run for each of the 100 wind fields in which the turbine was operating under normal conditions without earthquake shaking. In total 1,000 simulations were run; however, results of 550 simulations representing simulations earthquake loads applied simultaneously in a single horizontal direction to wind loads, and the wind only simulations are analyzed in this paper.

3. WIND TURBINE DEMAND MODEL

This study develops surrogate demand models, which are used to formulate the limit state functions used in reliability assessment, from simulated base moments and sectional bending moments at 61.3 m above the tower base. This second elevation is selected to evaluate the demand associated with excitation of the higher modes that has been shown to possibly lead to tower buckling (Nuta, 2011).

To remove any directional effects of the earthquake loading and wind turbine on the simulated results, a square root of the sum of squares (SRSS) of the moments in the *xz*- and *yz*-directions is taken at each time step. Demands models are fitted to the maximum SRSS values obtained per each simulation. The demand models form a mathematical expression that relates the base moment or bending moment at 61.3 m above the tower base to wind speeds and earthquake intensity measures. The models can also be used in the future to predict load effects without performing expensive numerical simulations. Given a level of wind speed v_m (m/s) and earthquake intensity IM, the predicted demand D_m can be represented approximately by a multivariate linear function:

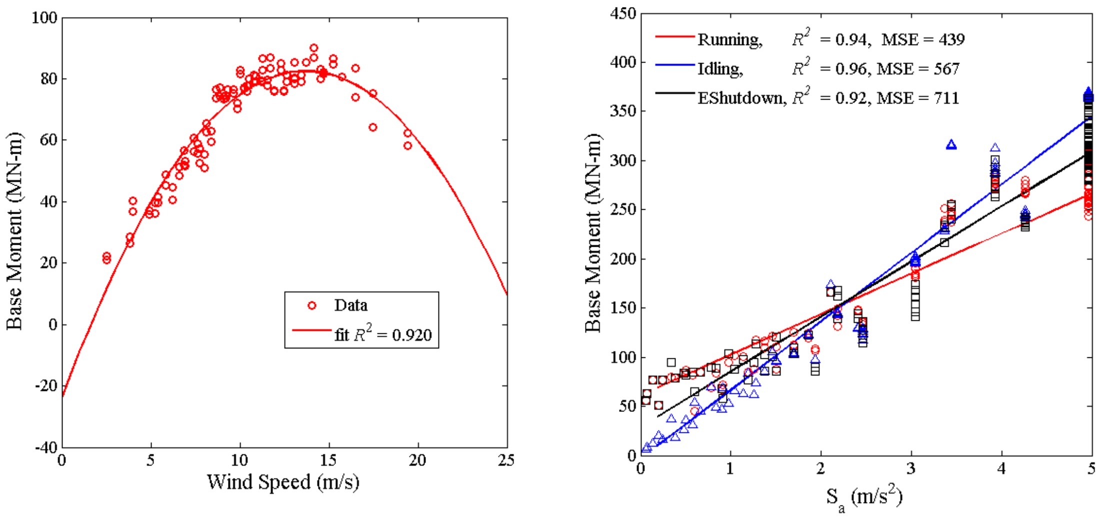
$$D_m = \alpha_0 + \alpha_1(v_m) + \alpha_2(IM) \tag{3.1}$$

where α_0, α_1 and α_2 are regression coefficients.

Table 3.1 provides the regression coefficients as well as the corresponding mean square error (MSE) and coefficient of determination R^2 for the base moments and sectional bending moment considering the wind turbine in a state of running, idling and earthquake-induced shutdown (EShutdown). Models for two intensity measures: peak ground acceleration (PGA) and the spectral acceleration S_a at the period the structure are shown. It is observed from all the coefficients that the influence of the wind on the response is insignificant as compared to the effects of the earthquake. This may be mainly due to the pitch control mechanism in this modern variable-speed wind turbine which causes the blades to furl at high winds, thus reducing induced drag forces on the tower. Figure 3.1a shows a quadratic fit for peak base moments from wind-only simulations. The figure clearly shows a decreasing response beyond the rated wind speed of 11.4 m/s as a result of the blade furling. In contrast, a linear function provides a good fit for the demand models when earthquake loads are added to the wind loads. For the model based on S_a, negative coefficients are obtained for wind speed. In case of the idling turbine, significantly lower coefficients are realized for the constant term as compared to the other cases. This observation shows that pitching of the blades is very effective in reducing rotor thrust and in turn tower loads, further supporting the need to consider aeroelastic behavior in load analysis for wind turbines. As such, the study regards the constant term and the wind load terms jointly as operational loads. Generally, both intensity measures appear to provide models with good R^2. However, S_a is an optimal intensity measure for turbine tower response with excellent R^2 values and relatively small MSEs. Figure 3.1b illustrates the goodness of fitness of the demand models to simulated responses from simultaneous earthquake and wind loading as functions of the spectral acceleration.

Table 3.1. Demand model coefficients (MN-m)

Scenario	Response	PGA(g)					S_a (m/s^2)				
		α_0	α_1	α_2	MSE	R^2	α_0	α_1	α_2	MSE	R^2
Running	Base Moment	70.8	0.6	181.4	2712	0.624	59.8	-1.8	50.3	438.6	0.939
	Bending Moment	23.0	0.3	58.6	246	0.657	21.0	-0.5	15.8	50.7	0.929
Idling	Base Moment	-4.3	2.3	297.5	4300	0.739	-4.6	-1.4	77.0	567.2	0.966
	Bending Moment	1.2	0.6	95.0	376	0.767	3.3	-0.6	23.9	87.4	0.946
EShutdown	Base Moment	35.2	2.5	214.2	3245	0.661	28.7	-0.3	57.4	710.6	0.926
	Bending Moment	13.7	0.7	67.9	251	0.717	14.4	-0.2	17.4	78.9	0.911



(a) (b)

Figure 2. (a) Base moment response showing blades furling at high wind speeds (no earthquake loads) (b) Demand models and simulated tower base moment

4. RELIABILITY ANALYSIS

Existing reliability theory allows the probabilistic performance of structural components such as the wind turbine tower to be represented by a limit state equation:

$$g(\mathbf{x}) = R - D_m \tag{4.1}$$

Where **x** denotes realizations of resistance R and load or demand D_m (Equation 3.1) random variables, which can include uncertainty in loads, turbine material properties, dimensions, design, construction and modeling errors. When the demand exceeds the resistance or capacity of the component, it undergoes a binary transition from a safe operating point to either a local or global failure. The probability of failure P_f for a given limit state, defined as $P_f = P\left[g(\mathbf{x}) < 0\right]$, can be efficiently estimated using simulation methods such as Monte Carlo Simulation and importance sampling techniques (Toft and Sørensen, 2011). However, for a well-behaved limit state first- and second-order reliability methods (FORM/SORM) provide an excellent approach to estimate the failure probability based on a reliability index β. By transforming the resistance and demand models, such that they are bivariate normally distributed with unit variance, the probability is given by $P_f = \Phi(-\beta)$, whereas the reliability index for $g(\mathbf{x})$ at a design point is given by $\beta = \mu_g / \sigma_g$, with μ_g and σ_g being the mean and standard deviation estimates of $g(\mathbf{x})$.

For structural safety purposes, the design equation for the wind turbine tower in an ultimate limit state following the load and resistance factor design (LRFD) format, which can be idealized by:

$$\phi R_n \geq \gamma_M M + \gamma_E E \tag{4.2}$$

in which R_n is the nominal flexural strength or capacity, ϕ is the resistance factor, M and E are the fraction of tower moment demand attributed to operational and earthquake load effects, respectively, and γ_M and γ_E are the partial load factors associated with the operational and earthquake loads, respectively. The resistance and partial load factors are evaluated corresponding to a target reliability at the limit state function given as

$$g(\phi R, \gamma_M M, \gamma_E E) = 0\,, \tag{4.3}$$

which relies on the mean, standard deviation and the probability distribution of each of the resistance and load variables. Note that the operational load *M* and earthquake load *E* in this study are estimated from the demand model based on coupled wind and earthquake simulations where $M = (\alpha_0 + \alpha_1(v_m))$ and $E = \alpha_2(S_a)$. This approach results in smaller values for *M* and *E* and diverges from that used by ASEC/AWEA (2011) and the IEC (2005-08) where the wind effect and seismic effect are derived independently. The nominal strength R_n of 196 MN-m and 121 MN-m which are determined based on provisions in the AWEA/ASCE recommended practices (2011), are used. The mean to nominal ratio of 1.07 and coefficient of variation (COV) of 0.15 (Ellingwood and Galambos, 1982) are applied to the computed nominal flexural strength. The occurrence of wind and earthquake events are estimated from annual wind speed data (DOE, 2011) and annual seismic hazard curves (USGS, 2008) for South California in the U.S., at a location defined by the coordinates 34.7º N and 118.5º W. This general area is chosen for this study because it has a good wind regime for wind energy developments and it is also an active seismic zone. The median S_a is estimated for the wind turbine tower with period *T* of 3.22 s from the median spectral acceleration at 1 s period S_1 using the expression: S_1/T. A lognormal distribution is assumed to characterize the annual S_a probability distribution. Table 4.1 provides the probability distributions and the parameters that are used to describe all random variables.

Table 4.1. Random variables for resistance and load parameters

Variable	Distribution	Median	COV (%)
Resistance, *R*	Lognormal	$1.07R_n$	0.15
Annual wind speed v_m	Weibull	7.0 m/s	0.20
Annual spectral acceleration S_a	Lognormal	0.057 m/s^2	1.38

By transforming the resistance and load variables to "equivalent" normal variables, the resistance and partial load factors are obtained from an unconstrained optimization approach based on Lagrange multipliers (Melchers, 1999):

$$\phi = 1 - \frac{\sigma_R \beta \delta_R}{\sqrt{\sum_i^3 \sigma_i^2}} \quad \text{and} \quad \gamma_j = 1 + \frac{\sigma_j \beta \delta_j}{\sqrt{\sum_i^3 \sigma_i^2}} \tag{4.4}$$

where *i* takes subscripts of *R*, *M*, and *E*, *j* takes subscripts of *M* and *E*, σ and δ are the standard deviations and the COVs of the resistance, operational load, and earthquake loads, respectively.

5. PARTIAL LOAD FACTORS

The IEC 61400-1 (2005-08) specifies partial safety factors of ϕ = 1/1.1 for ductile material strength and γ_M = 1.35 for loads in ultimate strength analysis under normal operation conditions without any consideration for earthquake events. Using the demand model in Figure 3.1 for wind-only simulations, the reliability of the 5-MW wind turbine tower is first estimated based on the IEC-specified partial factors. A reliability index β of 3.28 with a failure probability P_f of 5.1×10^{-4} is obtained making the tower reliable under normal operational loads. However, it is important to note that the wind only results reported here are unlikely to capture extreme demand values associated with fault load cases and may result in an under estimate of the failure probability. In the load analysis of structures such as buildings and bridges for extreme events including earthquake, a number of considerations including human safety, functionality and economic losses are made. Target reliability levels are chosen depending on the occupancy class, damage state or level of functionality of the structure desired after the occurrence of a rare event. Wind turbines are, more often than not, sited in areas with no or low human occupancy and as such the likelihood of injury or death of humans due to the failure or even collapse of towers is relatively small as compared to buildings and bridges. Consequently, high reliability indices equal to or above 3.28 may seem unreasonable even in the presence of seismic loads on towers. On the other hand, the towers as well as equipments they carry are very costly. Hence, wind turbines must be adequately protected against earthquakes to ensure minimal damage, low economic losses and quick restoration. Thus, this study computes different partial load factors under the loading conditions and assumptions previously stated to cover a wide range of target reliabilities, and to also test the sensitivity of these factors to different turbine states and types of response.

Tables 5.1 and 5.2 show the estimated load combination factors for various target reliabilities considering tower base moments and sectional bending moments at 61.32 m above the base. The resistance factor seems to be insensitive to the different scenarios - running, idling or earthquake – induced shutdown. However, the partial load factors for wind and earthquake effects are sensitive to the state of the turbine. Marginal differences are generally observed for all the three partial factors between the values considering the base moment and the sectional bending moment as limit states suggesting consistency in results. Furthermore, all the partial factors appear to be sensitive to the target reliability. For example, in combining loads for the tower of a running wind turbine, computed earthquake load effects are expected to be increased by 25% in order to achieve a 6.7% failure probability ($\beta = 1.5$) with respect to base moments. Reducing the probability of the these moments to exceed resistance to 0.05% ($\beta = 3.28$), which is the target reliability based on IEC 61400-1, requires the earthquake load effects to be increased by 55%. Computed operational load effects must be increased by at least 4%-9% to ensure that the strength of the tower is exceeded with probabilities below 6.7% ($\beta = 1.5$) for a running turbine or seismic-induced shutdown with respect to base or section moments. In the idling case, evaluated operational load effects should be reduced by factors ranging from 0.94 to 0.99 because of their insignificant contribution to demand as observed in previous section. As explained, resistance factors are computed based on a joint wind and earthquake approach using non-coded M and E, and as expected, are lower than IEC 61400-1 criteria for only operational load and resistance. The average partial factors for resistance, operational and earthquake loads at $\beta = 3.28$ are 0.55, 1.12 and 1.53, respectively.

Based on the partial factors computed for the three loading scenarios and the two structural limit states – base moment and moment at 61.3 m above the tower base, this study observes that Equation 5.1 could be used as a criterion for resistance, mean operational and earthquake loadings. The criterion corresponds to a structural reliability close to $\beta = 2.5$ with a failure probability of 0.6%. In choosing this target reliability, the low criticality in terms of risk and safety of the wind turbine tower during the occurrence of an earthquake as opposed to a building (usually with higher β) is considered.

$$0.70R_n \geq 1.1M + 1.4E \tag{5.1}$$

It is worth stating that the computed load factors are not comparable to the values provided in Equations 5.5 and 5.6 of the AWEA/ASCE recommended practices (AWEA/ASCE, 2011), which as previously noted have significantly different definitions of M and E.

Table 5.1. Partial factors for tower ultimate strength ϕ, operational load γ_M and seismic load γ_E considering tower base moment.

Reliability		Running			Idling			Seismic-induced Shutdown		
β	P_f	ϕ	γ_M	γ_E	ϕ	γ_M	γ_E	ϕ	γ_M	γ_E
1.5	6.7×10^{-2}	0.84	1.09	1.25	0.84	0.97	1.39	0.84	1.05	1.29
2.0	2.3×10^{-2}	0.77	1.11	1.33	0.76	0.96	1.52	0.76	1.07	1.39
2.5	6.2×10^{-3}	0.69	1.14	1.41	0.68	0.96	1.65	0.68	1.08	1.48
3.0	1.0×10^{-3}	0.61	1.17	1.50	0.60	0.95	1.78	0.60	1.10	1.58
3.3^*	5.1×10^{-4}	0.57	1.19	1.55	0.55	0.94	1.86	0.55	1.11	1.64

[*] IEC 61400-1 Target reliability

Table 5.2. Partial factors for tower ultimate strength ϕ, operational load γ_M and seismic load γ_E considering bending moment at 61.3 m above the tower base.

Reliability		Running			Idling			Seismic-induced Shutdown		
β	P_f	ϕ	γ_M	γ_E	ϕ	γ_M	γ_E	ϕ	γ_M	γ_E
1.5	6.7×10^{-2}	0.83	1.05	1.13	0.83	1.00	1.20	0.83	1.04	1.14
2.0	2.3×10^{-2}	0.77	1.07	1.17	0.75	1.00	1.27	0.75	1.05	1.19
2.5	6.2×10^{-3}	0.68	1.09	1.22	0.67	1.00	1.33	0.67	1.07	1.24
3.0	1.0×10^{-3}	0.60	1.11	1.26	0.59	0.99	1.40	0.59	1.08	1.29
3.3^*	5.1×10^{-4}	0.55	1.12	1.29	0.51	0.99	1.47	0.52	1.09	1.34

6. CONCLUSIONS

With the rapid growth of wind energy and developments of large scale wind farms in seismically active regions, this paper examined appropriate load and resistance factors for combining earthquake and operational loads in a reliability-based fashion. The National Renewable Energy Laboratory (NREL) FAST code is employed to adequately model a 5-MW wind turbine and generate dynamic structural responses, accounting for the aeroelastic behaviour of the turbine, when it is subjected to simultaneous stochastic wind loads and recorded earthquake time histories. Structural demand models for three operation scenarios – idling, running, and earthquake-induced shutdown – are developed from simulated results following an experimental design. Earthquake load has significant effects on the tower base moments and sectional bending moments at 61.3 m above the tower base. However, the influence of wind appears to be less significant due to the active pitch control employed by modern turbines. Nevertheless, operational loads in the running and earthquake-induced shutdown scenarios are considerable owing to significant rotor thrust.

Furthermore, the study adopts probabilistic models to describe the wind turbine tower resistance, annual winds and earthquakes in South California, U.S., along with analytical structural reliability techniques to evaluate partial load and resistance factors for meeting several performance objectives (target reliabilities). The investigation observes that whereas the resistance factor is insensitivity to the state of the turbine – running, idling or earthquake-induced shutdown, the partial factors for earthquake and operational loads are dependent on the turbine state. Identical factors are obtained for base moment and sectional bending moments. A target reliability of β = 3.3 with 0.05% failure probability, obtained on the basis of IEC 6100-1 criteria for operational loads and resistance (with no account of earthquake loads), yields partial factors of 0.55, 1.12 and 1.53 for resistance, operational and earthquake loads, respectively. The resistance factor is consistent with the provision in the IEC 6100-1 for ductile material strength. Considering the relative low criticality of wind turbines as compared to buildings with higher β values during an earthquake occurrence, the study identifies an approximate reliability of β = 2.5. This requires that 1.1 and 1.4 are, respectively, implemented as partial load factors for a fraction of moment demand attributed to operational and earthquake loads in addition to a factor of 0.7 for resistance in ultimate strength analysis as carried out in this paper.

Current provisions in the AWEA/ASCE recommended practices (AWEA/ASCE, 2011) for wind turbine structure requires that earthquake-induced effects are computed based on ASCE 7-05 (2006), thus considering response modification factors, importance factors and seismic response coefficient. However, the current study takes no account for these factors in determining earthquake loads, and uses coupled earthquake and wind simulations, unlike current standards which derive them independently, thus the reported partial load factors may not be directly applicable to code-based design loads.

Future research effort will focus on testing the sensitivity of the load and resistance criteria to different turbine configurations, site locations, probability distributions and distribution parameters. Also, the influence of uncertainty inherent in the system should be explored at the dynamic response simulation framework. Additionally, uncertainty resulting from modelling errors should be accounted. Future investigation will analyze load combination on the basis of design load provisions in existing design standards and concurrent stochastic loading processes for comparison.

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