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Wind Turbines and Seismic Hazard: A state-of-the-art review

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Abstract

Wind energy is a rapidly growing field of renewable energy and as such, intensive scientific and societal interest has been already attracted. Research on wind turbine structures has been mostly focused on the structural analysis, design and/or assessment of wind turbines mainly against normal (environmental) exposures while, so far, only marginal attention has been spent on considering extreme natural hazards that threat the reliability of the lifetime-oriented wind turbine's performance. Especially, recent installations of numerous wind turbines in earthquake prone areas worldwide (e.g., China, USA, India, Southern Europe and East Asia) highlight the necessity for thorough consideration of the seismic implications on these energy harnessing systems. Along these lines, this state-of-the-art paper presents a comparative survey of the published research relevant to the seismic analysis, design and assessment of wind turbines. Based on numerical simulation, either deterministic or probabilistic approaches are reviewed, since they have been adopted to investigate the sensitivity of wind turbines' structural capacity and reliability in earthquake-induced loading. The relevance of seismic hazard for wind turbines is further enlightened by available experimental studies, being also comprehensively reported through this paper. The main contribution of the study presented herein is to identify the key factors for wind turbines' seismic performance while important milestones for ongoing and future advancement are emphasized.

Keywords: Wind turbines, Seismic loading, Earthquake strong ground motions, Multi-hazard Environment, Dynamic Analysis, Structural response, Soil-structure interaction

1. Introduction

Energy consumption is growing constantly. The economic, social and cultural development of modern societies is becoming energy demanding and thus, it is an imperative to use alternative energy resources as a means to keep always stabilized the demand-supply balance. The conventional, though harmful for the environment, fossil energy sources including oil, coal and natural gas, are decreasing and their production cost is getting higher in several cases (e.g., offshore oil drilling or hydraulic fracturing in oil and gas wells). On the other hand, the low environmental footprint of the renewable energy renders it attractive to cover current and future energy demand. During the last decades, intensive research effort has been spent on developing innovative techniques and technological solutions that favor the sustainable energy production. Along these lines, wind energy, being already a mature renewable energy source, has a predominant role on the scene of the so-called "clear energy" production. According to the annual report provided by the Global Wind Energy Council (GWEC) [1], the global cumulative wind power capacity has been doubling almost every three years while it is expected to continue growing at a similar or even more aggressive rate. It is interesting to see that an increase of nearly 50% was observed for new wind turbines installations in 2014 reaching 51.477 MW of new wind generating capacity worldwide. The latter verifies the constantly increasing interest in wind energy investments, which exceeds globally $US80 billions only for 2013 [2]. Figure 1 presents the geographical distribution of the global installed wind power capacity while Figure 2 depicts the wind energy status for most of the European Countries by the end of 2013.

Such a rapidly growing energy field has already attracted scientific interest related to both the design and construction of wind turbines allowing for cost-efficiently harness of the perpetual wind power. From a structural engineering perspective, the primary objective is to design wind turbines that can adequately resist several exposures related to either harmful environmental conditions (e.g. wind, waves and currents) or even extreme natural hazards (e.g., earthquakes, hurricanes and tsunamis). The reliability analysis of wind turbines and the consecutive risk assessment are also essential in order to evaluate the vulnerability of this structural system and to quantify, mainly in terms of monetary losses, the adverse impact of the multi-hazard environment. Most of the times, wind forces subjected to the supporting tower and the rotor blades, are considered to be the primary design load while the common design load cases are related to both parked and normal operating conditions respectively. The emergency shutdown of the wind turbine can be accounted as a further “operational state”, which may be critical for the structural design or assessment of wind turbines. Moreover, depending on the location of these energy systems, a plethora of additional load cases has to be considered. For example, load cases related to the hydrodynamic forces (i.e., waves and currents), subjected to the tower, along with the wind-induced aerodynamic forces on the blades have to be calculated in case of offshore wind turbines. In order to describe the various load types, either deterministic or the more advanced probabilistic models have been applied in the literature (e.g., [3-6]) while reliability analysis has been also used to identify the failure rates of several wind turbines components as a means to draw up an efficient inspection and maintenance strategy (e.g., [7-15]).

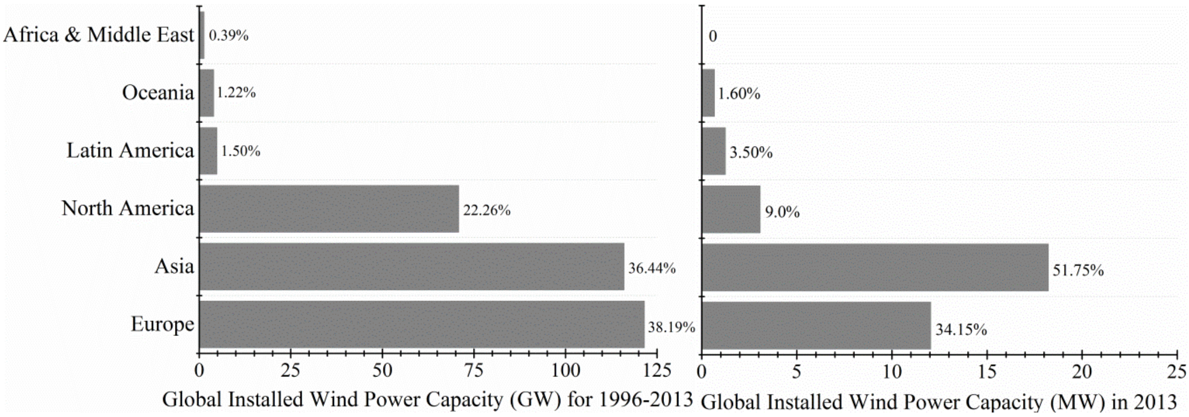

Figure 1. Geographical distribution of the global installed wind power capacity for the period 1996-2013 (left) and only for 2013 (right). Data were retrieved from GWEC [1].

Besides the aforementioned loading conditions, the vast spread of wind turbines installations around several areas worldwide has apparently broaden the hazardous sources that threaten this kind of infrastructure along its entire lifetime (up to 20-25 years). Therefore, demanding concerns have been recently raised related to the reliability of the wind turbines against a multi-hazard environment. Especially, an extensive number of wind turbines, either onshore or offshore, has been lately installed in earthquake prone areas, such as China, India and South Korea as well as in the US, Mexico and several seismic active zones of Southern Europe (e.g., Greece, Italy and Spain) and Middle East. It is interesting to note that China is currently at the forefront of the new wind turbines installations (Figure 1, right). Especially there is a huge increase over the last decade of more than 4600% in the wind power installed capacity and the strategic aim is to be tripled (approximately 200 GW) until 2020 [16]. Moreover, almost 6 GW of wind powered electricity is currently generated in the high seismicity area of California, ranked as the third largest wind power producer in the US [17]. Thus, it is becoming of high importance to elaborate the earthquake-resistant design of the new installations as well as the assessment of the existing wind turbines, since the seismic risk involved in these beneficial, though costly, investments for the societies has to be reasonably managed and mitigated.

Figure 2. Wind power installations in European countries by the end of 2013. Data were retrieved from GWEC [1].

The wind turbine is a high rise and slender structural system with a concentrated mass at its top (like an inverted pendulum); hence, it can be sensitive to lateral forces and deformations due to horizontal loading either from wind profiles or earthquake excitations. Although, there is a prevailing sense in the engineering community that earthquake loading is of limited relevance for wind turbines and hence, their hazardous environment is mainly considered to include the wind-driven horizontal forces. The reason for this notion may be founded on the limited number of wind turbines that have been observed, until now, to sustain severe damages after a major earthquake event, as in the cases of the 1986 North Palm Springs (CA, USA) [18] and 2011 Tōhoku (Japan) earthquakes [19-20]. Indeed, the long vibration period, usually identified for the normal wind turbines' support structures (e.g., from 1.5 s up to 12 s), corresponds to the earthquake strong motions part of low intensity (Figure 3). Hence, such a structural system is partially “self-isolated” from the most destructive part of earthquake excitations. The increased damping during the wind turbines operation (up to 5% of the critical damping or higher, [21-24] can further heal the excessive vibrations induced by seismic motions.

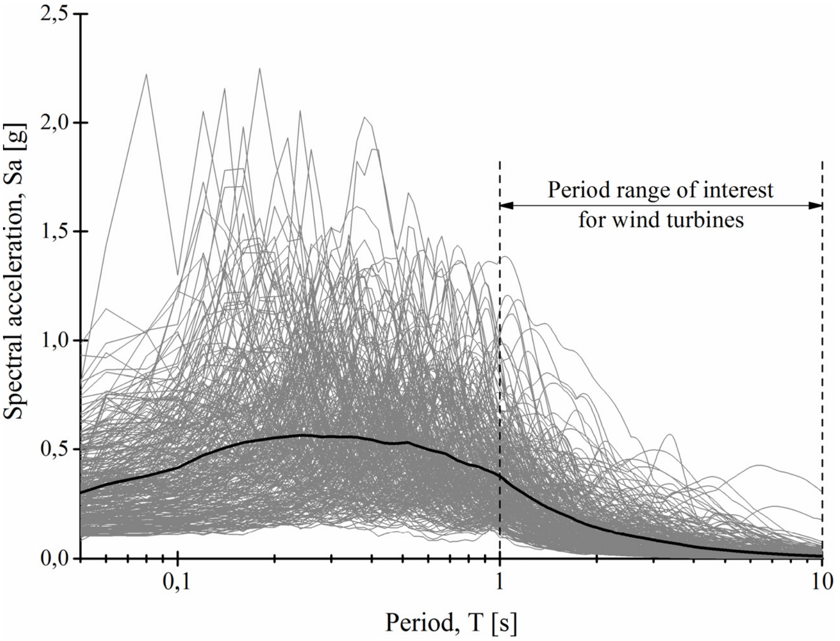

Figure 3. Elastic response spectra of 300 carefully selected seismic motions with a wealth of different characteristics in terms of both seismological (earthquake magnitude, source-to-site distance etc.) and strong ground motion (amplitude, duration, frequency content) parameters [159].

Nevertheless, this notion of “earthquake-proof” wind turbines can be proved seriously deceptive and hence, too risky unless a thorough evaluation of the seismic performance is carried out. Firstly, it is only 15 years (or even less) that extensive groups of modern wind turbines, or the so-called “wind farms”, have been installed in areas of high seismicity. Therefore, such a narrow experience cannot be considered as guarantee for the relevance (or not) of the seismic hazard in case of the wind turbines. Even in case that the seismic vulnerability for a single wind turbine is considered as low, the total risk of a wind farm, which contains a plethora of large, expensive, and homogeneous structures, is increasing due to the significant consequences (e.g., economic losses) derived from a common failure mode for the consisting wind turbines. It is recalled herein that the risk of an engineering system is composed by the vulnerability, expressed in a probabilistic way, and the (direct) consequences caused by system’s damages for a given exposure event [25]. Moreover, due to the specific cantilever-type configuration, wind turbines are lacking of significant redundancy; thus, the force redistribution mechanism, which normally relief the highly stressed parts of structures, is severely limited. As a result, local damages in critical areas (e.g., the supporting tower or the foundation structure) of a wind turbine subjected to earthquake excitation may be detrimental for the entire integrity of the infrastructure system. It can be also misleading to investigate the seismic relevance of wind turbines independently of the concurrent harmful environmental conditions. The seismic hazard has to be perceived as a part of an integrated multi-hazard environment rather than as an isolated exposure for wind turbines.

2. Objectives and Structure of the study

Based on the discussion made above, it is rather challenging for the researchers to scrutinize the impact of earthquake strong ground motion excitations on the structural performance and, the seismic reliability of wind turbines. Lately, several studies addressed the issue of the seismic assessment for this energy infrastructure while code provisions and technical guidelines include rather simplified considerations for the earthquake-resistant design of wind turbines. Along these lines, the objective of this paper is to present a detailed state-of-the-art review on currently available methods and published research that focus on the theoretical background, the modeling techniques and the analyses results concerning the seismic evaluation of wind turbines. In other words, the authors' basic intention is to provide both a conceptual survey of the research and a detailed synthesis of the applications addressing the seismic effects on the wind turbines. Hence, through a comparative assessment of the pertinent literature, the key factors for wind turbines' seismic performance are highlighted while milestones for further advancement and future practice are identified. It is notable that the current state of practice is marginally reviewed in this paper (mainly due to size limitations) and authors' intention is to provide separately a detailed survey for the existing code provisions regarding the seismic analysis and design of wind turbines.

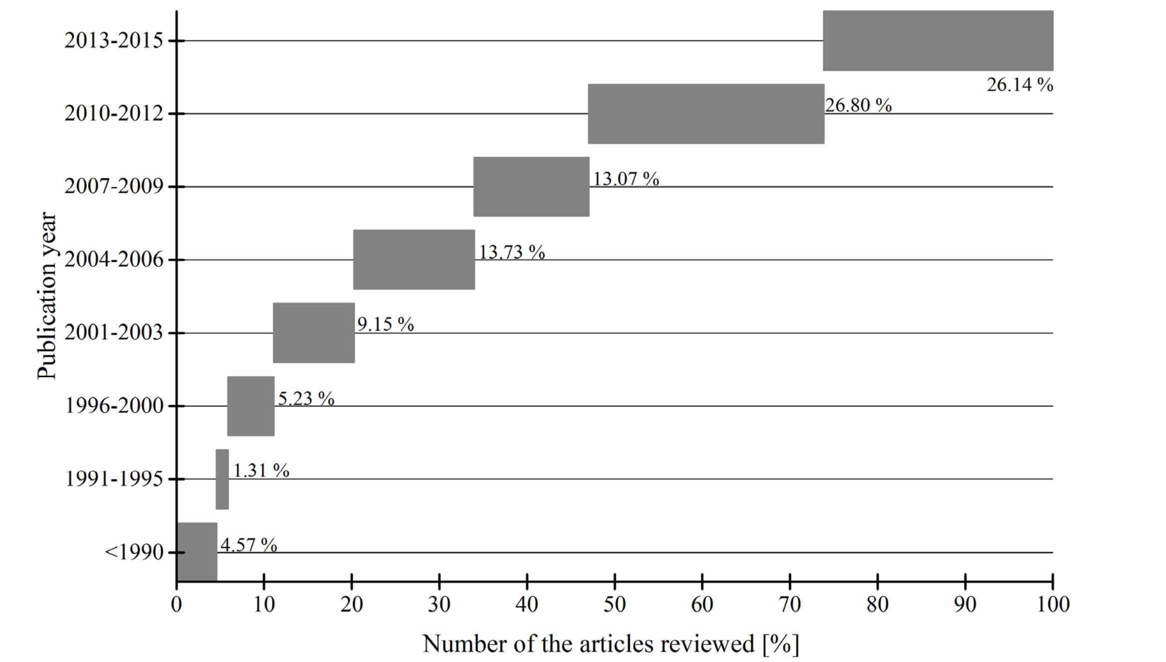

Figure 4. Distribution of the scientific articles mentioned herein in terms of the year of their publication.

This paper includes a thorough review of more than 155 scientific articles (e.g., journal papers, conference articles and technical reports) most of them (close to 90%) published after 2000 (Figure 4). Elsevier SCOPUS database of peer-reviewed literature and the Web of Science (WOS) were accessed to search for journal papers while the digital library of the Technical University of Denmark (DTU) was mainly the source to obtain conference articles and other technical reports. In order to structure the current study, the selected papers were primarily categorized according to the numerical (Section 3) or experimental basis (Section 4) they follow, the latter being rarely followed by the researchers (Figure 5, left) mainly due to the physical obstacles related to the experimental testing of such a massive and high-rise infrastructure. Furthermore, based on the statistical evaluation of the aggregated data shown in Figure 5, deterministic approaches were broadly applied to evaluate the seismic effects on wind turbines (Section 3.1) while only a limited number (i.e., 20%) of the articles reviewed herein favored the use of the more advanced probabilistic methods as described in Section 3.2. Special attention was also attributed to the soil-structure interaction effects (Section 3.3) that were found of primary importance for the dynamic response of such a slender structural system like the wind turbine. Finally, the list of conclusions, summarized in Section 5, enables gaining an overall insight into the current state-of-the-art status while it provides the critical points for future research addressing the wind turbines performance under the earthquake hazard.

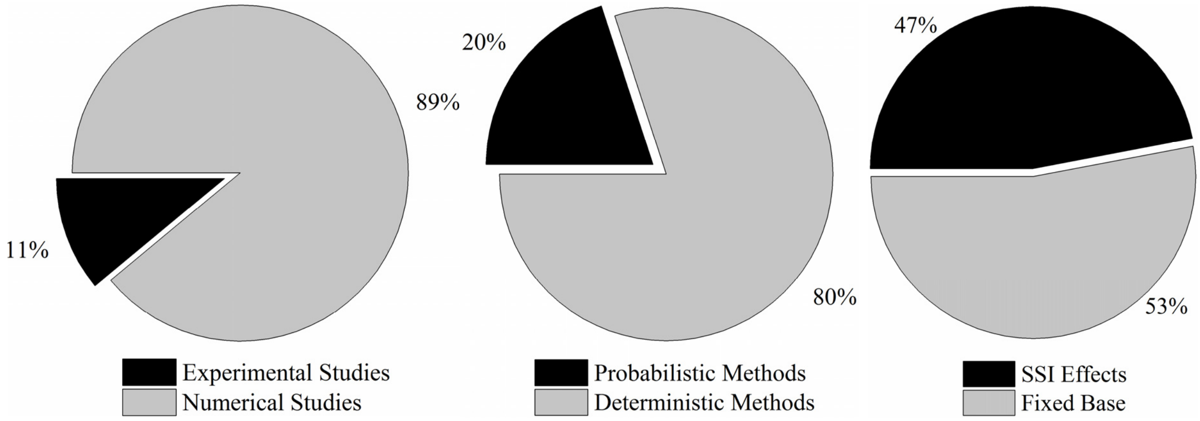

Figure 5. Different categorizations of the reviewed articles related to wind turbines under the seismic hazard.

3. Seismic evaluation of wind turbines based on numerical simulation

Earthquake strong ground motions that excite the wind turbines foundations during a seismic event constitute just a single component of the multi-hazard environment that threats these green energy harnessing systems over their life span. Commonly, the wind is considered as the primary load while, in case of the offshore installations, the exposure both to the sea waves and the currents can also affect significantly the wind turbines structural design. Moreover, other natural hazards, such as the hurricanes or typhoons, may have also detrimental effects on wind farms, lowering in such a way the expected benefits from these energy infrastructures that are normally associated with high investments either from the public or the private sector respectively. Several time-dependent degrading mechanisms [26-30] can further undermine the structural resistance of wind turbines like the fatigue occurring in critical joints of the supporting tower (e.g., [31,32]) or the seawater-induced (chloride) corrosion on the steel structural members (e.g., [33]). Motivated by such a demanding engineering problem, several researchers addressed the seismic effects on wind turbines based on either the more conventional deterministic approaches or by utilizing advanced probabilistic methods. The latter facilitates a consistent treatment of uncertainties and provides a basis for risk analysis and the determination of risk acceptance criteria [34].

3.1 Seismic analysis of wind turbines within a deterministic framework

Commonly, the seismic loads are quantified either via response spectra, which are associated with the modal response spectrum analysis (MRSA) or by the time-history representation of earthquake excitations, which are the required input motions for the more accurate method of response history analysis (RHA). Along these lines, the aforementioned analysis methods were applied by Bazeos *et al*. [35] to study the seismic response of a 37 m high wind turbine's steel supporting tower with the use of two different finite element (FE) models of varying refinement. First, a refined three-dimensional (3D) model, consisting of quadrilateral shell elements for the tower, was analyzed on the basis of standard normal superposition procedures using the elastic spectrum defined by the Greek Seismic Code [36]. The lowest reference peak ground acceleration of 0.12 g, prescribed by this seismic code, was adopted therein reflecting seismic forces expected for areas of low seismicity. Secondly, RHA was performed and a multi-degree of freedom (MDOF) oscillator with concentrated masses, located along the height, was subjected to six earthquake accelerograms artificially[1] generated to match the code spectrum. The almost perfect matching between the seismic motions' response spectra and the code spectrum led to nearly identical response results (i.e., accelerations and displacements at the tower's top) as derived from these two computational procedures (i.e., MRSA for 3D model *vs* RHA for simplified MDOF system). Moreover, the low seismic forces considered therein induced in critical points for the tower normal stresses lower than the maximum stress derived from static analysis with pseudo-static aerodynamic loads under wind survival conditions [37]. Such a dominance of the wind-induced design loads over earthquake loads of low intensity was corroborated by Ritschel *et al.* [38], who conducted a comparative assessment between the frequency and the time domain analysis method respectively in case of a wind turbine system with moderate height. Especially, the Nordex N80 wind turbine of 60 m high was modeled as a MDOF system and subjected to both the Eurocode 8 [39] elastic spectrum and acceleration time series, generated artificially in accordance with the aforementioned code framework. The response results showed that in terms of tower's bending moments these two structural analysis methods shared almost identical results at least for the upper half of the tower. However, close to the base, the MRSA method led to significant overestimation of the bending moment demand.

The frequency domain method was also adopted elsewhere for the seismic analysis of wind turbines. Lavassas *et al.* [40] as well as Baniotopoulos *et al.* [41] applied the Eurocode 8 [39] framework for MRSA to assess the seismic response of wind turbines with total height of 44.075 m and 76.15 m respectively. To this end, both simplified and detailed FE models were developed and common results were reached about the governance of the extreme wind case over the seismic loading, the latter being quantified by the code spectrum. Nevertheless, it should be noted that the response results derived from the spectral analysis method are highly depending on the definition of the design (i.e., code) spectrum. To be more specific, according to either European (e.g., Eurocode 8 [39]) or US design codes and technical guidelines (e.g., International Building Code [42] and ASCE/SEI 7-10 [43]), several parameters require determination in order to define the code spectrum. Based on Eurocodes notation, the importance factor, denoted by γ_I, and the behavior factor, q (or the response modification factor, R, in US codes) are critical parameters for the design spectral accelerations. Given, though, that the wind turbines are not directly addressed in the existing building codes and guidelines, such a selection of representative values for these factors is not straightforward. Lists for the behavior factor that can be found in most of the contemporary

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[1] For the sake of brevity, the current state-of-the-art methods for selecting and scaling earthquake records favor the use of three different categories of seismic excitations [160]: (a) real accelerograms, which have been recorded during past earthquake events, (b) synthetic motions simulated by theoretical models for the seismic fault rupture mechanisms and (c) artificial accelerograms calculated with the use of stochastic or random vibration theory methods to match a target response spectrum.

codes include a designation of q for inverted pendulum structures[2], which possibly constitute the closest structural configuration to the wind turbines. Based on this categorization and considering that wind turbines are designed to respond mainly in the elastic range, the Eurocodes-imposed upper bound of the behavior factor, q, ranges between 1.5 and 2 for steel structures with low dissipative behavior. Similarly, according to ASCE/SEI 7-10 [43], the response modification factor, R, assigned to an inverted pendulum type structure is taken equal to 2. It is, though, notable that intensive research is still necessary in order to quantify, either experimentally or analytically, the actual values of q that correspond with increased accuracy to the wind turbine systems.

Additionally, the importance class (or risk category for modern US codes) that wind turbines have to be assigned is another ambiguous issue. Based on the past practice, wind turbines generators were identified mostly as ordinary structures (Importance class II for Eurocode 8) that correspond to importance factor equal to γ_I=1.0 [44]. Nevertheless, since wind energy is constantly increasing as percentage of the global energy supply and modern societies are getting more dependent on this critical infrastructure, the relative importance of wind turbines needs possibly to be re-evaluated. Therefore, higher importance class may be selected (i.e., Eurocode 8: III or IV and ASCE/SEI 7-10: Risk Category IV for essential facilities) that corresponds to a range for the importance factor between 1.2 and 1.5. It is profound that the higher importance factors along with the low values of behavior factors, previously discussed, can severely amplify the seismic forces that have to be considered during the design or assessment process using the code-prescribed spectral analysis method.

The frequency-based analysis method is also sensitive in the damping ratio selected for the structural analysis of wind turbines. Within the MRSA framework, the system's damping is commonly considered identical to the damping ratio used to define the response spectrum, which, in turn, is usually calculated with 5% damping ratio on the basis of modern buildings codes' prescriptions. However, especially for parked wind turbines, the absence of the aerodynamic damping led the supporting towers to experience low damping, i.e., 0.5% - 2.0% of the critical damping [21,35,45-49]. Hence, the high fluctuation, which is commonly observed for the low damped response spectra, complicates further the application of the MRSA method, since most of the existing codes do not provide efficient methods to correct the damping level [50].

On the contrary, the time domain analysis method (RHA) accounts for the actual damping of the system, which consists mainly of the structural, aerodynamic and soil damping respectively. In particular, the total system's viscous damping ratio can be approximately expressed as a linear combination of the following three parts [51]:

$$\xi = \xi_{struct} + \xi_{aero} + \xi_{soil} \tag{1}$$

where ξ_{struct} is the structural damping (i.e., most of the times steel damping for the supporting structure of the wind turbine), ξ_{aero} is the aerodynamic damping, whose source is essentially the spinning rotor aerodynamics, and ξ_{soil} is the damping developed in the interface between the soil medium and the foundation system. The radiation damping, ξ_{rad}, due to the radial propagation of waves from the structure's oscillation can be considered as an additional

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[2] According to Eurocode 8 (§5.1.2.1) [41], an inverted pendulum is defined as a system in which: (a) 50% or more of the mass is located in the upper third of the height of a structure or (b) the dissipation of energy takes place mainly at the base of single building element. A similar definition for this structural system can be found in ASCE 7-10 (Ch. 11) [45].

damping source while, in case of offshore wind turbines, the drag between water and structure produces the hydrodynamic damping, ξ_{hydro}. Contrarily to the last two damping components (ξ_{rad} and ξ_{hydro}), both the aerodynamic and soil damping may seriously modify the total system's damping. The latter can be efficiently captured only through the time domain analysis method since, as previously discussed, for the frequency domain method the system's damping is usually considered fixed to the damping ratio adopted to calculate the reference spectrum [24].

Along these lines, Witcher [52] found that the typical damping ratio of 5%, involved in a code-based MRSA to define the design spectrum, led to significantly lower response for the supporting structure of a parked (and hence low damped) wind turbine in comparison with the response results derived from the more accurate time domain analysis method. Only in case of an operating wind turbine (e.g., 5.0% of critical damping), the response results obtained through MRSA and RHA were found quite similar [52]. Therefore, design spectra with two different damping ratios (e.g., 0.5% and 5.0% for the parked and the operating conditions respectively) should be theoretically used when the frequency domain method is to be applied for the seismic evaluation of wind turbines. Besides the operational state (parked *vs* operating conditions) that differentiates the damping to be adopted for a wind turbine analysis [53], the direction of the earthquake base excitation in comparison to the wind direction may also alter the effective damping [54] and hence, the application of the MRSA is hindered additionally for the case of wind turbines.

On the other hand, the superiority of the time domain over the frequency domain analysis is credited due to the geometrical and material nonlinearities found to affect wind turbines' dynamic response especially for the ultimate limit state [55] while the former analysis method allows for accurate modeling of the complex aeroelastic interaction among the different components of this infrastructure. More specifically, the time-dependent operation of both the controller and the safety system, commonly installed in a modern wind turbine, can be efficiently modeled within the framework of a RHA and thus, for example, the shutdown triggered by specified nacelle acceleration is efficiently simulated. Moreover, the continuously changing conditions of wind turbines, i.e., operation under normal wind profiles, the emergency shutdown due to excessive vibrations and the parked (idling) case because of excessive wind speeds, can be thoroughly investigated within a time domain method. This analysis procedure is further preferred in order to calculate the response (i.e., time series for acceleration or displacement) of nacelle and the rotor blades, since these critical components of wind turbines may be severely influenced by the concurrent influence of both the horizontal and the vertical earthquake excitations [38], efficiently treated within the RHA framework.

Furthermore, the time domain analysis has been recently favored by the boost of the computational power along with the parallel evolution of engineering software. Therefore, RHA constitutes nowadays a robust method to design and/or assess with increased accuracy complex or unconventional structural systems and as such, several researchers have already adopted this analysis method in order to evaluate the seismic performance of wind turbines installations. Along these lines, Wang & Zhang [56] developed two different FE models for a 1.65 MW wind turbine of 70 m high. For the first model, shell finite elements were used both for the rotor blades and the supporting tower while the blades were considered as lumped masses for the second and more simplified model. Both the models were excited by just a single strong ground motion, which is the widely known El Centro seismic wave (El Centro Earthquake, 1940) scaled to peak ground acceleration, PGA, of 0.51 g. Comparing the seismic response obtained from the aforementioned models, higher dissimilarity was found for the displacement time history, calculated at the top of the turbine's tower, and the normal stress at the turbine's base. Nevertheless, a common finding was valid for the maximum lateral displacement at the top that exceeded 1 m (or 1.43% drift) revealing, in such a way, the dominant role of the seismic action for the design of wind turbines located in earthquake prone areas. Similar investigation was also carried out by Ishihara & Sarwar [46], who studied the seismic response of two horizontal axis upwind turbines with rated powers of 400 kW and 2 MW (36 m and 67 m of high respectively). For each wind turbine two models were developed, i.e., a simple one considering the rotor blades as lumped mass and the full blades-tower FE model. RHA was performed with artificially generated seismic motions that were closely matched to the target response spectrum prescribed by the Building Standard Law of Japan [57]. Based on the results from this study, the authors concluded that the contribution of higher modes is becoming of increased importance for the seismic response of the large wind turbines. Hence, a FE model, which accounts for the aerodynamic coupling between the rotor and the tower, has to be adopted for the RHA of contemporary wind turbines. Furthermore, the seismic response (i.e., base moment and base shear) of the wind turbines studied therein was found highly varying that is associated with the large inherent uncertainty (randomness) of the seismic motions. The latter highlights the necessity to adopt transparent earthquake records selection strategies based on state-of-the-art methods (reviewed recently by Katsanos *et al*. [58]) as a means to obtain reliable response results.

The relevance of the seismic hazard for the wind turbines has been also highlighted by several other studies. Studying the seismic response of wind turbines via RHA of "blades-tower-foundation" integrated FE models, He & Li [59] as well as Song *et al.* [60] concluded that the influence of the earthquake excitations on wind turbines is far from negligible; hence, seismic analysis should be prioritized for the design and/or assessment of these energy systems located at seismically active areas. Especially, based on Song *et al.* [60] investigation, the seismic demand for the lateral displacement at the top of a wind turbine's tower, subjected to a far-field seismic wave with PGA of 0.224 g, was found to exceed over 40% the lateral displacement limit state according to the Chinese code for high-rise structures excited by seismic motions (GB50135 [61]). Additionally, the Greek Seismic Code [36] was adopted by Stamatopoulos [49] to define the earthquake loading for the seismic evaluation of a 53.95 m high wind turbine. The analysis results revealed an insufficient code-based design especially for earthquake-prone areas that are susceptible to near-fault excitations. It is briefly mentioned that the near-fault strong ground motions are composed by short-duration pulses with excessive ground velocity that expose structures to high energy input at the beginning of the seismic event and hence, impose higher demand on structures compared to the ordinary far-fault ground motions (e.g., [62-65]).

Furthermore, Kim *et al*. [66] identified the seismic vulnerability of a conical concrete foundation system assumed to support a large offshore wind turbine of 5 MW located close to the west coast of South Korea. The seismic design of this infrastructure system, modeled in details with both plate and beam finite elements, was performed according to modern Korean design codes (i.e., Korea Port and Marina Design Code [67], Korea Bridge Design Code [68]) and the analysis results indicated excessive tensile stresses in the concrete foundation near the bracket and the piles-concrete foundation interface. Hence, additional reinforcing may be required for the entire foundation system. A similar type of a large concrete bucket foundation was also analyzed in the time domain by Zhang *et al*. [69]. They developed a detailed FE model, which was excited by three strong ground motions selected on the basis of the Chinese design code. Despite the low intensity that these seismic motions were scaled to (i.e., PGA=0.1 g), potential earthquake-induced liquefaction of the underneath soil was detected that could adversely affect the overall stability of the wind turbine system studied therein.

For most of the already reviewed studies, the significantly limited number of seismic records (one up to three), which were adopted to perform RHA, along with the uncertainty inherently involved in the earthquake-induced strong motions [70] may undermine the reliability of the obtained structural response results [71]. Hence, in order to diminish the bias in the seismic demand estimates, Asareh & Volz [72] performed linear and nonlinear RHA of a contemporary wind turbine with the use of 22 earthquake far-fault motions, each consisting of two independent horizontal components. Furthermore, an aeroelastic simulator (Aerodyn [73]) was applied to calculate the aerodynamic forces exerted on the blades of the horizontal axis wind turbine for each time step of the finite element simulation while wind fields of varying amplitude were appropriately generated (TurbSim [74]). Accounting for the variation both in the wind profiles and the earthquake motions adopted, 2112 RHA were conducted and it is interesting to note that the maximum seismic base moment was calculated for wind conditions, which correspond to the rated wind speed (11.40 m/s) of the wind turbine adopted therein. Moreover, seismic motions with 5% damped spectral acceleration, $Sa(T_1, 5\%)$, higher than 0.20 g was found to induce nonlinear response (in terms of lateral displacements) mainly occurred for the higher elevations (i.e., over the first 20 m) of the supporting tower, where the steel cross-sections are smaller than the base.

The critical effect of the earthquake loading on these energy infrastructures has been further corroborated by the detailed research of Alati *et al.* [75], who studied the seismic response of an offshore horizontal axis wind turbine assumed with either a tripod or a jacket supporting system. Particularly, a multi-hazard environment was considered under the combined exposure of wind, wave and earthquake while the latter was represented by 49 pairs of strong ground motions horizontal components recorded during past seismic events. Fully coupled, nonlinear time domain simulations were conducted with the use of 3D models that account for the rotor blades, nacelle, control system as well as the supporting structures and the underneath pile groups. A thorough investigation of the structural response results showed that the contribution of the earthquake loading, even for moderate levels of PGA, increased significantly the demand that was already obtained due to the normal environmental cases (i.e., wind and waves of various profiles). The latter was more profound for the moment demand at the base of the supporting structure and the axial force at the piles head. Additionally, the wind-wave-earthquake hazardous environment induced higher structural response estimates than the ones associated with typical design load cases prescribed by the design standards IEC 61400-3 [76] for offshore wind turbines. Although the analysis results presented by Alati *et al.* [75] are limited to a particular wind turbine system considering only site-specific loading conditions, the importance for undertaking an accurate seismic design is highly emphasized, since the earthquake load was found governing the design load cases.

Analogous conclusions have been also drawn for onshore horizontal axis wind turbines indicating that earthquake demands may be design driving in different areas worldwide of increased seismic hazard. Based on numerical analysis, Prowell [77] assessed the implications of the seismic loading for a range of land-based wind turbines with rated power from 65 kW up to 5 MW. Time domain simulations were performed on the basis of full FE models (i.e., including blade rotors and the supporting tower), subjected to both turbulent wind fields and earthquake acceleration time histories for non-operational (i.e., parked), operational and emergency shutdown scenarios. Increased confidence was obtained for the results calculated therein, since 99 pairs of horizontal components of real earthquake records were reasonably selected from the PEER-NGA Database [78] in order to account for a variety of seismological (i.e., magnitude and source-to-site distance) and strong ground motions parameters (i.e., intensity and frequency content) respectively. In total, more than 2000 linear RHA were conducted and the combined wind-earthquake hazardous environment induced, on average, significantly higher structural demand (i.e., moment and shear forces at the tower base) than extreme wind events defined elsewhere [79,80]. The latter was valid for all the three operational conditions referred above while the parked conditions were mostly affected by the earthquake excitations due to the absence of the aerodynamic damping from the spinning rotors. Only the blades bending moment was almost remained unaffected by the seismic excitations even when they were associated with extremely rare earthquake events of high intensity.

The different operational conditions, already identified to be critical for wind turbines' structural performance, along with the aerodynamics and hydrodynamics effects, the latter being valid only for offshore installations, render this energy harnessing infrastructure an unconventional structural system in contrast to the most common for the structural engineers, buildings and bridges. The dynamic response of wind turbines was found to be further complicated by the seismic effects and hence, the use of elaborate modeling techniques is essential in order to predict the structural demand with increased accuracy. As already reviewed, several researchers developed refined FE models using advanced FE codes and computer aided engineering software, i.e., OpenSees, Abaqus, Ansys and SAP2000, that facilitate performing RHA for wind turbines of various scale subjected to different exposures. Despite the fact that these widely used FE method-based programs include well-established codes to simulate the seismic excitation and the corresponding dynamic performance of structural systems, they usually lack of a fully coupled modeling that considers concurrently all the different effects possibly acting on wind turbines (e.g., gravity forces, aerodynamics, hydrodynamics and seismic excitation). To this end, special software such as ADAMS-WT [81], FAST [82], Flex5 [83], HAWC2 [84,85] and Bladed [86], may significantly accommodate wind turbines' integrated modeling. The majority of these wind turbines-dedicated codes adopts the so-called multi-body simulation (MBS) approach (e.g., [87]) that enables to model all the critical parts of turbines (e.g., foundation, tower, nacelle and blades) as a series of continuous, flexibly or rigidly inter-connected discrete units preserving, at the same time, reasonably low number for the required degrees of freedom (DOFs). For the sake of clarity, FAST (Fatigue, Aerodynamics, Structures and Turbulence, [82]) software package, released by the National Renewable Energy Laboratory (NREL), uses a combined modal and MBS formulation as a means to simulate in time domain the complex dynamic behavior of a wind turbine. Bladed [86] shares similar formulations and modeling techniques with FAST, since the modal representation is used to model the flexible parts of wind turbines. The MBS approach serves also the basis for the ADAMS-WT (Automatic Dynamic Analysis of Mechanical Systems – Wind Turbines, [81]) code, which adopts lumped masses connected by springs-type elements to model the flexible bodies of a wind turbine (i.e., the rotor blades and the supporting tower). Moreover, a fully nonlinear calculation of dynamic response is provided with the use of Flex5 [83], where few DOFs are necessary to model the turbine. More details about the aforementioned aeroelastic software packages, some of them already supported by special codes to model implicitly the seismic loads, can be found elsewhere (e.g., [88-91]).

The MBS approach has been found efficient to model and analyze wind turbines exposed to a multi-hazard environment (e.g., [92-95]). Along these lines, a hybrid MBS approach was applied to calculate the structural response for a 1.50 MW wind turbine of 65 m high under the combined wind-earthquake loading [96]. Time domain analysis was performed and the bending moment at tower's base was found to be remarkably affected even by a weak earthquake excitation (i.e., PGA=0.056 g) when the turbine is spinning. Furthermore, Hänler *et al.* [97] favored the use of the MBS approach and hence, the supporting tower and the blades of a wind turbine with height equal to 60 m were modeled as interconnected bodies with a limited number of DOFs. Normal operation conditions were considered at the rated wind speed (13 m/s) for the particular wind turbine while a single artificial accelerogram scaled to PGA=0.305 g was generated on the basis of Eurocode 8 elastic spectrum. Results from the time domain seismic analysis indicated that for normal wind loading, 80% of the total vibration (modal) energy was associated with the first tower's mode. On the other hand, due to the earthquake excitation, only 54% of the tower's energy was related to the first mode implying that tower's higher modes are becoming of high importance in seismic analysis. Similar conclusion has been drawn elsewhere while the higher rotor blades modes, captured only by a full system model, were also found important for the seismic response since they may correspond to the region of maxima spectral accelerations [46,47,75,98]. With such a motivation to study an integrated blades-tower-foundation model subjected to the seismic loading, Jin *et al.* [99] utilized the MBS approach and an artificial accelerogram (PGA=0.36 g), which was imposed to perform RHA, induced high fluctuation (over 180%) for the section forces (i.e., bending moments and axial force) mainly at the tower's base. This variation in critical demand measures due to the sudden earthquake occurrence was found to disturb the wind turbine performance in terms of energy harness signifying the adverse seismic implications on wind turbines even in case of no imposed structural damages.

3.2 Seismic analysis of wind turbines within a probabilistic framework

Wind turbines and their complex dynamic behavior are subjected to various sources of uncertainties associated with the structural and the soil material properties, the modeling, analysis and design assumptions as well as the multi-hazard environment that these energy infrastructures are exposed during their lifetime. However, the deterministic methods, mostly adopted to evaluate the structural response of wind turbines, materialize a rough and simplified treatment of the uncertainties involved. Hence, the reliability of the analysis results is seriously questioned. On the contrary, only a marginal incorporation of probabilistic methods has been already detected in the literature that allow for a reasonable quantification of all the uncertainty sources associated with this challenging engineering problem.

Firstly, Kiyomiya *et al.* [100] developed a probabilistic procedure concerning the concurrent exposure of wind turbines both to wind loads and earthquake excitations. The Weibull probabilistic distribution was applied to represent these two hazardous components and the exceeding probability at a certain intensity value for the earthquakes or the wind events was obtained through their joint probability density function. Furthermore, an onshore wind turbine of 1650 kW and 60 m high was studied with the use of a detailed FE model that accounts for the wind turbine's steel tower and the pile foundation supported by the soil media underneath. The wind loads were considered through pseudo-static horizontal forces while a single seismic excitation, recorded during the Great Hanshin (or Kobe, Japan) earthquake in 1995 with PGA=0.692 g, was used for the time domain analysis. Regarding the dynamic response results, only linear performance was identified for the supporting steel structure. However, the acceleration calculated at the tower's top exceeded 1.530 g and this significant amplification (more than twice) of the maximum input acceleration may cause disorder or even damage in the fine-tuned equipment of nacelle. The latter has been also verified elsewhere [101]. Moreover, amplification of similar scale was calculated for the tower's lateral displacements while the wind conditions associated with the rated wind speed (i.e., 11 m/s - 15 m/s) maximized the dynamic response. The seismic capacity was also found quite adequate even for large earthquake events and thus, the wind-induced loading was considered therein to be the governing design case. It is, though, noteworthy to mention that the aforementioned results are restricted to the particular case-study, which is an early-stage wind turbine of small scale subjected, through the numerical simulation, only to a single strong ground motion.

The low probability identified by Kiyomiya *et al.* [100] for the simultaneous occurrence of large earthquakes and extreme wind conditions (i.e., storms or hurricanes) renders overconservative to consider extrema in an additive form for both wind and seismic-induced loads. Thus, Mensah *et al.* [102] found reasonable to provide a probabilistic basis for combining the earthquake loads with the operational wind loads, the latter being representative for three operating scenarios, i.e., running, parked (idling) and earthquake-induced emergency shutdown. A contemporary wind turbine was considered in this study with rating power and total height equal to 5 MW and 90 m respectively. The FAST code [82] was utilized to model the turbine while a large variety of generated wind fields (TurbSim [74]) and real strong ground motions composed a wide set of exposures including both frequently occurring scenarios as well as those which are highly unlikely. Response results from 550 analyses in the time domain showed that the influence of wind loading is significantly less as compared to the seismic effects. The latter can be partially attributed to the pitch control mechanism that causes the blades to furl at high speeds and thus, the induced drag forces on the tower are remarkably reduced. Existing structural capacity models along with demand models, derived therein after regression analysis on the numerical simulation response results, were coupled with the annual probability load distributions in order to assess the reliability for the particular wind turbine under the operational and earthquake loads. To this end, the first order second moment theory (FOSM) and the first order reliability method (FORM) [103-104] were applied and, contrary to the calculated partial resistance factors, the load factors were found sensitive in the turbine's state (i.e., running, idling or earthquake-induced emergency shutdown). It is notable that the latter findings were found valid for different levels of reliability, quantified by Mensah *et al.* [102] with the use of the reliability index, β.

Pérez Rocha *et al.* [105] conducted also reliability analysis for onshore wind turbines assumed to be located in several Mexican territories. Especially, the combined exposure environment of wind and earthquake actions was considered therein via a probabilistic framework that accounts for local seismicity and wind speeds models. The main outcome of this study includes a set of maps that relate the different regions of Mexico with the estimated reliability index, β, for wind turbines, which were either assumed with common resistance for all the country regions or optimally designed according to a cost-related criterion [106,107]. Based on those maps, the seismic action was found to be more detrimental for wind turbines' reliability compared to the wind loads implying that, at least for moderate-to-high seismicity areas, earthquake considerations should be involved into wind turbines design and/or assessment. Locations exposed to similar hazards, i.e., the west coast of USA and the Gulf of Mexico, were also selected by Mardfekri & Gardoni [108] to apply an advanced probabilistic framework for the multi-hazard risk assessment of offshore wind turbines. Along these lines, novel probabilistic models were developed for deformations as well as shear and moment demands of wind turbines' supporting towers subjected to multiple exposures like wind, wave, currents, turbine operational loadings and earthquake excitations. These demand models were calculated by updating available models with the use of additional virtual experimental data [109,110] obtained from time domain analyses of detailed 3D nonlinear FE models of wind turbines subjected to the aforementioned sources of exposures. To this end, a comprehensive experimental data design was materialized using the Latin hybercube sampling technique [111] as a means to create a set of representative configurations (i.e., geometrical and material properties for the wind turbines, their foundation system and the soil underneath) providing in such a way an adequate coverage of the common design space. An efficient calibration for the derived probabilistic models was also implemented with the use of Bayesian techniques and the fragility of a modern 5 MW wind turbine of 90 m high was finally assessed on the basis of the already derived demand models. As confirmed also elsewhere (e.g., [72,100]), higher vulnerability for the turbine's tower was calculated for the operational conditions related to the rated wind speed than the cut-in and cut-out speeds, the latter two define the wind speed range, within which a turbine is operating and producing power. Nonetheless, the contribution of wind loading to the wind turbine's fragility was found insignificant compared to the one derived from the seismic excitation and this is valid even for low intensity earthquake events. The fragility analysis, conducted by Mardfekri & Gardoni [108], highlighted also the governance of the bending over the shear failure mode respectively as normally anticipated for slender structural systems like the wind turbines. Moreover, coupling the fragilities with the annual probability density functions for seismic and wind hazards related to the selected sites (Mexican Gulf and Californian coast), the obtained probability of complete damage was found higher than the nominal annual failure probability of 10^{-4}, prescribed by DNV-OS-J101 [112] as the target safety level for wind turbines' support structures and foundations. It is finally noteworthy to mention that the increased seismicity of USA west coast led to higher risk of failure for wind turbines in comparison with the extreme wind speeds (i.e., hurricane) considered for the Gulf of Mexico.

Similar to the aforementioned study, the fragility analysis was also adopted elsewhere in order to evaluate the seismic risk of wind turbines. Along these lines, Nuta *et al.* [113] applied the incremental dynamic analysis (IDA) method, introduced by Vamvatsikos & Cornell [114], in order to calculate the seismic fragility of an 80 m high tower that supports an 1.65 MW wind turbine. Shell elements were used to model only the supporting tower, since both the nacelle and the rotor blades were excluded by the numerical simulations. Furthermore, a uni-hazard environment consisting only of the seismic exposure was considered and three sets of seismic motions were formed in order to quantify the seismic hazard of Los Angeles, Eastern and Western Canada respectively. Several demand measures were adopted on the basis of deformations (peak displacements and rotations) and normal stresses while the damage states, required to calculate the fragility curves, were related both to the functionality and the repair cost of a wind turbine after the occurrence of a major earthquake. Based on the analysis results, low seismic risk was revealed for both the Canadian areas (i.e., Victoria, BC and Southern Ontario). On the other hand, the Los Angeles area was associated with much higher seismic risk for the wind turbine tower, still, though, moderate at the intensity level of the design earthquake prescribed by ASCE/SEI 7-05 [115]. Low vulnerability was also identified for a 5 MW offshore wind turbine of 90 m high, for which the seismic fragility was numerically assessed by Kim *et al.* [116] via both inelastic static (pushover) and incremental dynamic analysis respectively. However, the exclusion of the aerodynamic effects from the dynamic analyses of the wind turbines, subjected to a limited number of seismic motions, may bias the outcome of the aforementioned two studies, in which the concurrent exposures (e.g. winds, waves and operational loads) to the seismic hazard were also waived.

3.3 Soil-Structure Interaction effects and other special considerations

Early research has shown that the dynamic response of tall and slender structural systems, like industrial chimneys, water towers or spillway towers in dams, can be seriously affected by the soil compliance mostly in case of moderate stiff or soft soil profiles with shear-wave velocity, v_s, lower than 750 m/s [117-119]. Regarding the wind turbines, the interaction between their foundations (e.g., monopile systems, tripod and jacket structures, suction caissons as well as gravity-based foundations, [120]) and the surrounding soil media has been recently identified as a critical aspect for analysis and design purposes since it exerts severe influence on the dynamic behavior of these energy harnessing systems installed either inland or offshore (e.g., [24,121,122]). More specifically, both the mode shapes and the natural frequencies of a wind turbine may be changed due to the soil-structure interaction (SSI), which also affects the overall system’s damping depending mostly on the foundations properties and the height of the turbine [123]. As a result, several researchers (e.g., [124-127]) have already introduced advanced approaches to account for the SSI effects in case of wind turbines while their seismic behavior has been also found of high relevance with this dynamic interaction.

On the basis of numerical simulations, an efficient method to account for the SSI phenomena is to substitute the soil-foundation system with a set of springs and dashpots, which are expected to model the inertial forces that are transmitted from the dynamically excited superstructure to the foundation soil (i.e., inertial interaction, [128]). Along these lines, the first investigation of a wind turbine’s dynamic behavior under the influence of SSI was conducted by Bazeos *et al.* [35], who introduced a set of linear springs and dashpots at the soil-foundation interface of the FE model developed therein. According to the eigenvalue analysis results, the fundamental frequency of the supporting tower structure was significantly lower (more than 10%) for the flexible than the fixed-based system while even wider influence of the SSI was identified for the higher vibrations modes in terms of their shapes and the corresponding natural frequencies. Similar results that corroborate the importance of considering the SSI effects on the dynamic performance of wind turbines have been also reached by several other studies, where either linear or nonlinear laws were adopted for the spring elements (e.g., [19,49,59,96,97,99,129]). Along these lines, the compliance of a wind turbine’s soil-foundation system was employed by Taddei & Meskouris [130] with the use of a lumped parameter model that consists of six uncoupled springs, one along each of the six degrees of freedom. No dashpots were considered and the stiffness coefficients of the generalized spring elements were calculated independently on the seismic excitation frequency. The findings obtained therein verified the sensitivity of the turbine’s tower dynamic characteristics in the SSI phenomena (i.e., reduction in tower’s natural frequencies). Furthermore, the seismic analysis, based on the time domain approach with the use of artificial accelerograms, showed an almost perfect agreement in the response results associated with either the simplified, springs-based substitute model for the SSI or the more accurate BEM (boundary elements method) model, implemented also by Taddei & Meskouris [130].

Besides the SSI-induced shift of the natural frequencies, the soil flexibility was also found of high relevance for the seismic response of wind turbines. Based on Alati *et al.* [75] investigation, maxima demands in terms of bending moments at the blade root were found highly increasing with soil compliance while the latter has been additionally verified in case of offshore platforms subjected to environmental-induced dynamic loading (i.e., wind, currents and waves, [131]). A springs-based model was also utilized by Kim *et al*. [116] when they assessed the seismic fragility of offshore wind turbines. More specifically, a multi-layered soil profile was considered and the pile-soil interaction was represented with the use of spring elements with varying nonlinear constitutional laws based on the stiffness of the different soil layers existing from the seabed up to the tip of piles' foundation. It was found important to apply such a detailed, soil layers-based modeling approach of SSI otherwise the seismic fragility might be underestimated for certain types of offshore wind turbines.

Nevertheless, higher refinement is provided for the SSI quantification when the entire soil domain, surrounding and supporting the wind turbines foundation system is modeled appropriately through finite elements that enable capturing the complex dynamic interaction between the soil and the structure. Such a holistic approach, still computational demanding, was adopted by Kjørlaug *et al*. [101], who used 3D eight-node solid elements to model the soil underneath and surrounding the pile foundation of an inland wind turbine. Eigenvalue analysis was performed for the entire FE model (i.e., superstructure, monopile foundation and soil domain) and the more flexible the soil domain was ($100 \leq v_s \leq 1000$ m/s), the higher deviation was observed for the first natural frequency compared to that of the fixed-based model. Furthermore, the seismic analysis that was performed via RHA of the FE model using a seismic motion of varying amplitude showed the sensitivity of wind turbine's dynamic response in the soil profile underneath. Particularly, for moderate-to-high strong ground motion intensity (i.e., PGA ≥ 0.30 g) and for soft soil conditions (i.e., v_s=300 m/s), the seismic response, which was quantified in terms of lateral displacement and turbine's base moment, was calculated higher than the wind-induced dynamic response. The reverse pattern was observed for stiffer soil profiles (v_s=500 m/s), where the wind loading was the driving load case.

A detailed 3D model of the entire soil-foundation-wind turbine system has been also developed by Mardfekri & Gardoni [108,109,132], who adopted nonlinear constitutional laws to represent both the soil behavior and the soil-pile dynamic interactions. Particularly, the Mohr-Coulomb plasticity model was utilized to define the nonlinear behavior of soil media and an elastic-plastic Coulomb model along with advanced modeling techniques (i.e., use of "contact pairs" provided by ABAQUS) were adopted to describe the nonlinear response of the soil-pile contact. Such an advanced modeling of soil-foundation system was favored therein, since the conventional methods used to quantify the SSI effects, i.e., the Winkler [133] elastic foundation models or the *p-y* curves adopted by Reese & Wang [134] to design pile foundations for wind turbines, were found to result in inaccurate dynamic response results [135]. The latter was profound for the large pile sizes typical of the offshore wind turbines. The high computational sources required for the dynamic analysis of the entire FE model (i.e., consisting of the wind turbine along with the underneath soil-foundation system) did not inhibit other researches from applying this time-costly procedure to elaborate the SSI effects on wind turbines seismic performance (e.g., [41,69,100,136]). Along these lines, Prowell *et al*. [137] showed that soil compliance can affect the maximum seismic demand distributions (in terms of bending moments and shear forces) along the elevation of a 90 m high wind turbine's tower; hence, the turbine design in earthquake-prone areas may be severely influenced by SSI. Particularly, the increased demand calculated mainly for higher elevations of the wind turbine studied therein under the assumption of soft soil conditions, may impose special considerations for the seismic analysis and design of a large and contemporary wind turbine, for which the vibration frequencies and modes shapes were also shifted due to the SSI effects [138]. Moreover, the serviceability performance of wind turbines operating under day-to-day wind loads can be predicted with increased accuracy, since the detailed consideration of the SSI phenomena and the soil flexibility enable calculating reliable estimates of lateral displacements at the top of the support structures [139]. Hence, the resulting probability of exceeding specific drift thresholds (i.e., serviceability limits) can be beneficiary for the wind turbines' manufacturers.

Unlike the soil-foundation compliance and its widely identified effect on the wind turbines response, there are pertinent issues that have attracted limited research attention and hence, their contribution in wind turbines seismic performance is still highly controversial. More specifically, the earthquake-induced vertical excitation of wind turbines has been scarcely considered during the seismic analysis and design process. Firstly, Ritschel *et al.* [38] reported that comparing the normal design loads (IEC [76]) and the earthquake loads associated with the vertical excitation, the latter may provoke higher response especially in the upper part of a wind turbine. Hence, the performance of the complex and ultra-sensitive equipment located at the turbine's hub (e.g., nacelle, rotor, blades and pitch control mechanism) can be adversely affected. The earthquake-induced vertical excitation induced also tilt vibrations that amplified the tower's base bending moment demand. However, just a single vertical strong ground motion component was utilized for the time domain analysis of the wind turbine studied by Ritschel *et al.* [68] and consequently the aforementioned results need further validation. Few other studies [113,140,141] have also addressed this issue and especially, Kjørlaug *et al.* [101] found that nacelle experienced high vertical accelerations, which were excessively amplified from the initial vertical motions subjected at the tower's base. It is notable that for soft soil conditions (i.e., v_s=300 m/s) the input vertical acceleration was found amplified nearly three times at the nacelle's point while even higher amplification factor (close to eight) was calculated for almost rocky foundation conditions (v_s=1000 m/s). As a result, this excessive amplification of vertical accelerations over wind turbine's elevation along with the large mass, which is normally concentrated at the hub's height, resulted in high vertical inertial forces mostly observed in the critical interfaces between nacelle and tower as well as tower and base.

Finally, marginal effort has been also spent to evaluate the influence of the earthquake excitation angle on the wind turbines dynamic response [38,113,142] and hence, no solid conclusion can be practically drawn on this issue.

4. Experimental evaluation of wind turbines seismic response

Physical restrictions, technical obstacles as well as funding limitations, being reasonably associated with the experimental seismic testing of large infrastructures like the modern wind turbines, have significantly narrowed the pertinent research activity mainly in a numerical framework. As discussed above, the vast majority of studies that addresses the seismic evaluation of either onshore or offshore wind turbines are based on analytical methods including advanced mathematical formulations, FE models and numerical simulations. However, there are still few cases reported in the literature, where the seismic performance of a prototype wind turbine was assessed via large-scale experiments. Along these lines, a series of full-scale tests was conducted at the University of California San Diego (UCSD) for the uni-axial seismic excitation of a 22 m high wind turbine with rated power of 65 kW [47]. Base shaking was imparted perpendicular to the axis of the spinning rotor using the Large High Performance Outdoor Shake Table (LHPOST [143]), which was provided by the

Network for Earthquake Engineering Simulation (NEES). A limited number of real earthquake motions, scaled in various intensity levels, was used for the seismic excitation and the main intention was to avoid inducing excessive nonlinear response (and hence severe damages) to the prototype wind turbine. Despite the fact that this experimental program included testing of an early-stage wind turbine, which is small both in size and capacity and an active control of blade pitch is also missing to regulate rotor's speed, significant insight was obtained on the seismic behavior either in operational conditions or in idling state with low winds (2-4 m/s). Moreover, analysis of the experimental results was performed to infer the dynamic characteristics (i.e., natural frequencies and mode shapes) and the damping properties of this wind turbine while its seismic demand was captured by dense instrumentation, placed uniformly on this asset.

Especially, the reliability of the particular experimental setting was granted since the experimentally estimated natural frequencies and mode shapes were closely matched with those derived by the numerical simulation of the specific wind turbine modeled with finite element techniques of varying refinement [47]. Moreover, marginal sensitivity of the wind turbine's dynamic characteristics was detected in its operational state (i.e., spinning or idling rotor), which, on the contrary, was found to affect the seismic response especially in terms of the accelerations and displacements profile along the turbine's height. As expected, the higher damping, being normally associated with the operational state of spinning rotor (i.e., aerodynamics effect), reduced the seismic demand, which was also influenced by the direction (i.e., fore-aft and side-side) that the ground shaking was subjected to the aforementioned test specimen [53]. Additionally, in agreement with previous findings (e.g., [46]), the seismic demand for the particular wind turbine of limited height and energy capacity was found to be primarily governed by the first-mode response [144] while the latter is not valid for the modern and higher turbines, in which the higher modes are expected to have significant contribution to the demand parameters (e.g., [97]).

Besides the detailed experimental study conducted by Prowell and his collaborators, Zhao *et al.* [145] addressed the seismic excitation of wind turbines using a shaking table provided by the State Key Laboratory of Disaster Reduction in Civil Engineering at Tongji University, China. Four seismic motions were selected as the required input motions for the dynamic tests while a prototype turbine of 96.52 m high was scaled down with a factor equal to 1/13. Thus, the height of the model tower was equal to 7.42 m and analogous size reduction was also materialized for all the components of the particular wind turbine specimen (e.g., nacelle, rotor and blades). White noise tests were used to estimate experimentally the first two natural frequencies of this wind turbine model. Moreover, along with the seismic excitation imposed through the shaking table, the rotating velocity of the blades was set to three levels of 0, 15 and 30 rpm respectively and as expected, the higher spinning velocity considered, the lower seismic response was calculated due to the increased aerodynamic damping.

Contrarily to the limited studies that address experimentally the seismic response of wind turbines, significant research work has been already focused on identifying the dynamic properties and the structural demand of these critical infrastructures through field measurements on the basis of various loading conditions. Along these lines, ambient vibrations due to several environmental effects or impact loads have been mainly used to extract the dynamic characteristics of either early-stage on-shore wind turbines (e.g., [146-148]) or more contemporary installations with increased size and capacity (e.g., [77]). Structural health monitoring techniques have been also adopted to provide long-term recordings of wind turbines structural response during normal operational conditions (e.g., [149-151]) while full-scale static tests for wind turbine's tower were recently conducted to evaluate its flexural buckling strength and critical failure modes [152]. Moreover, wind tunnel tests have been reported in the literature as a means to identify the aerodynamic behavior of a small wind turbine [153] while the efficiency of either passive (i.e., a novel tuned rolling-ball dampers [154]) or semi-active (i.e., use of smart magnetorheological dampers along with a control algorithm, [155,156]) vibration control systems was evaluated using a scaled turbine's model excited on a shaking table provided by the Technical University of Denmark (DTU). Notwithstanding the advancements already made regarding the experimental testing of wind turbines, it is necessary to extend these applications also for offshore installations, for which the concurrent exposure to several hazardous sources (i.e., wind, waves, currents and earthquake) may significantly enrich the field measurements and hence, structural response identification will be further facilitated.

5. Conclusions and recommendations

The present state-of-the-art review provides a comparative evaluation of the already released research being pertinent to the seismic implications that are currently becoming of high importance for wind turbines. Extensive installations of these green-energy harnessing systems in earthquake prone areas drove several researchers to scrutinize the seismic analysis and design of wind turbines by utilizing either frequency or time domain methods considered, most of the times, within a deterministic framework. On the contrary, probabilistic approaches, being credited for the systematic quantification of the inherent analysis and design uncertainties, have been marginally incorporated by the studies already conducted in this challenging engineering field. Hence, intensive effort should be spent in order to prioritize advanced probabilistic methods that enable the detailed risk assessment of wind turbines against a multi-hazard environment. Moreover, the current research advancement is mainly numerically-bounded and thus, the valuable experimental validation should be further pursued to identify the critical aspects of wind turbines' seismic performance.

A solid conclusion from the studies reviewed above is that the seismic hazard has a significant role to play in the structural analysis, design and/or assessment of wind turbines, since response quantities and reliability over the lifetime of these infrastructures were found to be severely affected by the earthquake strong ground motions. Plenty of cases were documented through the literature, where the seismic excitations were found to be the design driving load case, even prevailing over the detrimental effects of the wind-induced horizontal forces. Beyond this primary outcome, such an enlightening of the interrelation between earthquake excitations and wind turbines emerged several critical aspects, which are briefly summarized in the following:

- An integrated framework consisting of the seismic hazard and other concurrent exposures should be considered either for design purposes or when wind turbines' risk is to be assessed. Otherwise, the analysis results obtained may be misleading, since the seismic demand has been found to be influenced by simultaneous adverse actions.
- The use of full FE models, including the nacelle and the rotor blades, the supporting tower as well as the soil-foundation system, along with time domain analysis is highly favored in order to capture adequately the complex dynamic behavior of wind turbines. Higher-modes effects, aerodynamic interaction between the supporting tower and the rotor blades as well as the nonlinear soil behavior and the foundation compliance are marginally treated with the conventional simplified, linear models.

- A variety of mature computational codes and specialized software have been already released incorporating advanced approaches that allow modeling of several phenomena associated with the wind turbines' dynamic performance (e.g., aeroelastic interaction, hydrodynamics effects in case of offshore installations). Nevertheless, most of the wind turbines-dedicated programs are currently missing a consistent and precise treatment of the earthquake loading; hence, refinement is still necessary.
- Due consideration should be paid to the SSI phenomena, since the soil compliance and the earthquake-induced inertial interaction between the superstructure and the soil-foundation system may significantly modify the dynamic characteristics of a wind turbine and its seismic response.
- The dynamic response of wind turbines is diversely affected by their operational states (i.e., normal operating conditions, parked state and emergency shut-down due to excessive loads) and the related phenomena (i.e., aerodynamic damping due to spinning rotor). Therefore, these different conditions should be reflected when the wind turbines are to be analyzed and clear load combination rules have to be developed.

Additionally, a series of topics is presented below that has to be comprehensively addressed on ongoing and future research for wind turbines and their seismic relevance.

- Following the current trends for taller and massive wind turbines of increased capacity and cost [157,158], it is of high priority to elaborate the seismic vulnerability of these recently launched energy systems, since the vast majority of the pertinent research already undertaken refers mainly to early-stage and lighter wind turbines with shorter height and lower capacity.
- The installation of wind turbines with gradually increasing size in areas of high seismicity raises scepticism about the adequacy of the current foundations systems. Hence, advanced techniques of modeling and analysis should be adopted to scrutinize the demanding foundation structures and the soil underneath. Moreover, special issues like scouring or the earthquake-induced liquefaction observed especially at the sea bed, where the offshore wind turbines are installed, need additional refinement.
- A state-of-the-art-based strategy to select and scale earthquake strong ground motions is a requirement to obtain reliable response results using the time domain analysis of wind turbines. Emphasize should be given to the frequency content of the seismic records that will be used selected for RHA while the effects of vertical or near-field earthquake excitations on wind turbines seismic demand should be further investigated.
- The seismic resistance of wind turbines may be adversely affected by time-ageing phenomena and deterioration of critical structural components that increase the susceptibility to severe damages and hence, induce significant monetary losses. As a result, advanced methods consisting of analytical models for various deterioration sources (e.g., corrosion, fatigue) along with time-dependent estimations for the structural capacity should be incorporated in a lifetime-oriented, multi-hazard risk assessment of wind turbines.

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