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COMBINATION RULES OF EARTHQUAKE AND AERODYNAMIC LOADS FOR SEISMIC DESIGN OF WIND TURBINES

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Abstract

The use of wind turbines for renewable energy production has gained considerable relevance in the last 2 decades, especially in countries prone to Earthquakes (Mexico, Chile, USA, Japan, etc.), mainly due to cost reduction and their positive environmental impact. The rapid development of this industry has led to the constant growth of the wind turbines size (tower height, rotor diameter and nominal power). Therefore, the suitable understanding of the structural behavior requires a careful analysis in order to predict the expected maximum loads for seismic design purposes.

One of the most controversial aspects in seismic design of wind turbines has been how to combine seismic and aerodynamic loads when these actions are assessed in an uncoupled way (seismic load assessed through spectral modal analysis). ASCE/AWEA RP2011 [5] recommends combining both loads applying a reduction load factor of 0.75 to the direct sum (for steel towers). Asareh [9] and Santangelo et al [10] have proposed that the combination of seismic and aerodynamic loads with load factor of 0.75 can provide results sufficiently close to the coupled response. However, Prowell [7] and Meng et al [8] have shown that the combination rule proposed by ASCE/AWEA underestimates the response, and the square root of the sum of the squares (SRSS) gives better results compare to the coupled response (for steel towers). International codes such as IEC 61400-1 [3] and GL [6] establish that both loads must be combined applying a load factor of 1.0 to the direct sum. Lately, IEC 61400-1-2019 [4] has proposed that when seismic load is evaluated through response spectrum method, then the aerodynamic load is added using the SRSS method. Regardless these specifications provide some seismic guidance typical wind turbine guidelines are not intended to provide a deep seismic understanding therefore the seismic issue is not properly addressed.

This work presents a comparative analysis between coupled response of seismic and aerodynamic loads and their uncoupled analysis. Coupled simulations have been carried out with the FAST open software (time-history analysis) considering the new generation of large turbines supported on steel, concrete and hybrid towers. On the other hand, seismic uncoupled response has been evaluated using FAST and SAP2000 software separately. For seismic analysis, several accelerations records generated by different seismic-tectonic mechanism have been used (shallow crustal, subduction interface and subduction intraplate sources). The results obtained shows a high dispersion on data, which is highly dependent on the wind turbine type (fundamental period and dynamic response), seismic-tectonic source (frequency content, strong motion duration) and the relative weigh between seismic and aerodynamic loads. Based on our results, a new proposal of combination rules of seismic/aerodynamic loads is made, which provides a better matching between coupled and uncoupled response.

Keywords: Wind turbines, seismic loads, aerodynamic loads, load combinations, FAST.

1. Introduction

In the past two decades, wind energy has increased its worldwide total installed capacity from 24 GW in 2001 to 651 GW in 2019 [1]. This grown is explained both because of decrease of wind energy generation cost and environmental attractive. To increase energy production, the industry has developed taller towers and bigger rotor diameter, also installing wind farms in new regions even seismic active regions. While previous Wind Turbines (WT) barely reaches 1-MW and did not exceed 80 m height to hub nor total mass of 150 ton, current projects include towers taller than 140 m in active seismic regions such as Japan, Chile, China, North America, etc., and a variety of materials for towers: steel (traditional towers), concrete, and hybrid concrete-steel in a variety of weights. In Fig. 1 the growth of WT over the years and a picture of wind turbine with its main components.

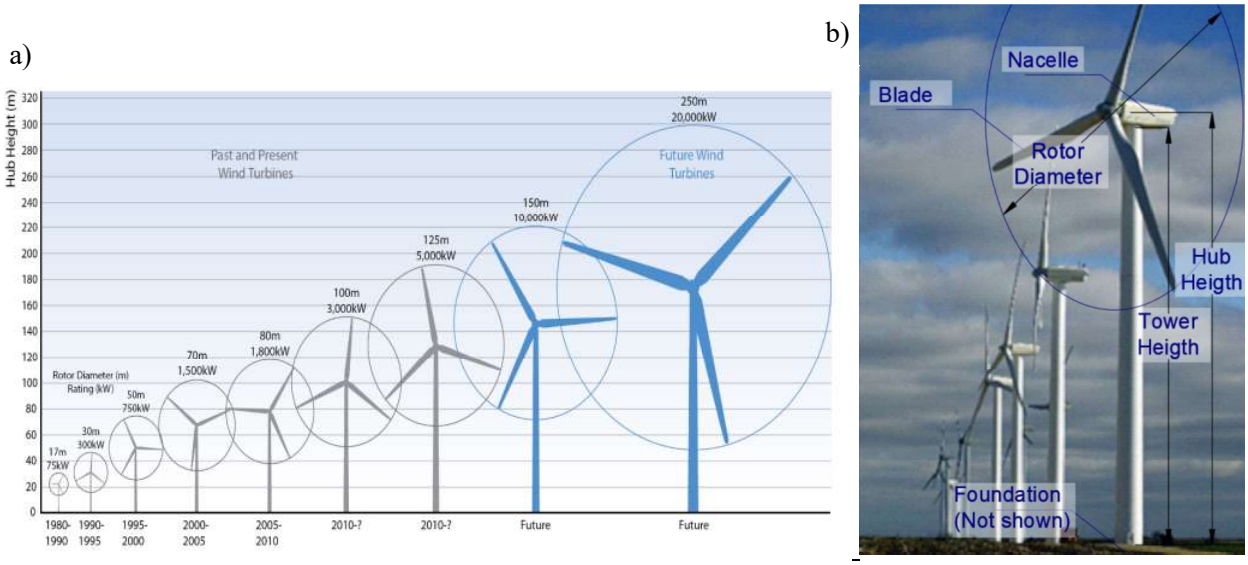


Fig. 1 – (a) Wind Turbines dimensions over the years [2], (b) WT main components and dimensions

This incremental in height and weight of WT, as well as its location in seismic areas, requires a correct modeling of the interaction of wind and seismic motion, as the simultaneous occurrence of both loads is expected. Nevertheless, neither guidelines for wind turbines are specialized in seismic design, nor many seismic codes deeply attend WT seismic behaviour. In this respect, one of the most controversial aspects in seismic design of wind turbines has been how to combine seismic and aerodynamics motions.

Current practice estimates on the one hand wind load with specialized software for aerodynamics loads, and the other, earthquake response obtained by structural software or even self-developed tools for response-spectrum analysis. As the simulations are not usually simultaneous (or coupled) the combination of wind loads (W) and earthquake response (EQ) depends on the criteria adopted. The load scenarios for EQ verification in WT are: parked or idling case with minor W (1% structural damping), operational case with W (1% structural + 4% aerodynamic = 5% damping), and shutdown case with W and forced rotor stop triggered by the earthquake (5% damping). About W, typical values are between average wind velocity (Vave ~7m/s) and rated wind velocity (Vr ~11m/s) [3, 4].

About modeling of WT for seismic loads, main WT guidelines are: IEC61400-1 [3, 4], ASCE/AWEA [5] and Germanischer Lloyd (GL) [6]. Typically a FEM (Finite Element Model) representation by response spectrum approach is required, where FEM simplifications are sometimes permitted [3, 4], however frame elements for tower with masses of rotor and nacelle located eccentrically is the most common FEM model. The damping, as indicated in previous paragraph, is assumed to be 1% for parked or idling situation, and 5%

in operational condition because of aerodynamic damping addition. These damping values has been calibrated experimentally [7], nevertheless can vary according to the particular conditions [7, 8].

Regarding the uncoupled combination of W and EQ for WT, ASCE/AWEA [5] indicates 0.75·(EQ+W) as a recommended practice, while IEC61400-1 [3] and GL [6] combined those as direct sum i.e. 1.0·(EQ+W) combination. A variety of research has focus on the combinations rules without consensus, some using numerical simulation tools as FAST open software (National Renewable Energy Laboratory NREL), and other experimental data as a full-scale 65 kW WT test in 2004 at the University of California, San Diego using the Network for Earthquake Engineering Simulation (NEES) [7]. Asareh [9] and Santangelo et al [10] have proposed that the combination of seismic and aerodynamic loads with load factor of 0.75 can provide results sufficiently close to the coupled response. However, Prowell [7] and Meng et al [8] have shown that the combination rule proposed by ASCE/AWEA underestimates the response, and the square root of the sum of the squares (SRSS) gives better results compare to the coupled response (for steel towers). In the Table 1 the characteristics of mentioned studies are summarized, where all towers are made in tubular steel sections.

Table 1 – Previous investigation on EQ and W coupling for WT

Author(s) Year	Analysis	Wind Turbine and tower					Wind speed and turbulence	Seismic motion
		WT class	Hub Height	Rotor Diam.	Total Mass	Fund. Period		
Prowell (2011)	Experimental full-scale / FAST	65 kW HAWT-3	22.6 m	16 m	10.7 t	0.59 s	0.8 - 5.5m/s	6 EQ records from: CAL (3), TR (1), CA (1) and TW (1).
	Ambient Vibr. / FAST	900 kW HAWT-3	55.0 m	53.6 m	110 t	1.75 s	5.0 m/s ± 2.1 m/s.	No seismic input.
	Ambient Vibr. /FAST	1.5 MW HAWT-3	70.0 m	72.0 m	194 t	2.48 s	8 - 15 m/s	No seismic input.
	Numerical FAST	5 MW HAWT-3	90.0 m	126 m	699 t	3.22 s	11.4 m/s (Mean) turb. level B (IEC)	99 ground motions from PEER/Luco.
Asareh (2015)	FAST - NonLinear	5 MW HAWT-3	90.0 m	126 m	699 t	3.13 s	2 m/s-20 m/s, turbulence level B (IEC)	22 EQ scaled from: CAL (13), TR (3), JP (2), TW (2), IT (1), IR (1).
Santangelo et al. (2018)	FAST	5 MW HAWT-3	90.0 m	120 m	699 t	3.16 s	5 m/s-20 m/s, medium turbulence (IEC).	10 EQ from: CAL (6), JP (1), TW (1), TR (1) and IT (1).
Meng et al. (2020)	Experimental 1/100 scale	16 W HAWT-3	67 cm	48 cm	1.2kg	0.13 s	2.5m/s-7.0 m/s	10 EQ scaled at PGA (0.1g-1.0g) from: CAL (9) and JP (1).
	FAST	1.5 MW HAWT-3	64.7 m	70 m	-	-		
HAWT-3: Horizontal Axis Wind Turbine, 3 bladed. CAL: California, USA; JP: Japan, TR: Turkey; TW: Taiwan; IT: Italy; IR: Iran; CA: Canada.								

In order to study the relation between coupled EQ and W response, a set of WT are modeled in FAST platform and SAP2000 v21 software, considering a variety of strong ground motions (Instrumental records) and wind simulations.

2. Wind Turbine Model

To estimate coupled and uncoupled response, a numerical study for a commonly used 5MW Horizontal Axis Wind Turbine (HAWT) installed on four different towers is performed. Numerical simulators considered are FAST v.7 (Fatigue, Aerodynamics, Structures, and Turbulence) open source aeroelastic simulator platform and SAP2000 v21 FEM software. They are used as follow:

- FAST v7: coupled response (EQ+W) and W response (Time history analysis or TH)
- SAP2000 v21: EQ response (Time history analysis or TH)

FAST is an open source simulator developed by Jonkman, & Buhl [11] at the National Renewable Energy Laboratory (NREL) that employs a combined modal and multibody dynamics formulation in time-domain. FAST simulation is complemented by other routines to calculate the aerodynamic loads as TurbSim to simulate wind profile load. Asareh & Prowell [12] implemented a seismic module for FAST code defining a base (or platform) oscillator at tower bottom with mass, stiffness and damping properties, and applying time-history motion up in three directions: two horizontal and one vertical. This implementation is not the direct way used to solve the equation of motion in dynamic of structures, and those mass, stiffness and damping values for platform must be calibrated according to mass and highest frequency of WT, as well as the required precision [12].

In order to incorporate the inertial and elastic properties of WT tower in FAST, unitary mass and section stiffness are assigned at each of the defined tower height fractions, to later be interpolated by FAST. For blades a similar characterization is realized and is well-described in [13]. As tower properties are not directly defined for each tower section in detail, but interpolated, mass adjustment of ±5.5% and stiffness calibration ratio ranging from 0.91 to 1.15 were applied. Otherwise rotor and nacelle properties as position, mass-inertia, stiffness and damping are directly defined in FAST and are described in [13]. Dynamic properties of tower are reduced to two Fore-After (FA) modes and two Side-to-Side (SS) modes, modal shapes are input for FAST and are represented as 6th order polynomial formulation to fit modal shapes (obtained from SAP2000 model), also inherent structural damping is set as 1% of the critical while aerodynamic damping is inherently calculated by FAST. A similar procedure is carried out for blades defining two flap modes and one edge mode.

SAP2000 is well-known FEM software developed by CSi Company, optimized to structural analysis and design. A 3D model is defined, with frame variable-section elements for tower and rigid links to locate rotor and nacelle centre of mass. Blades are not incorporated but its mass only. FEM is loaded with dead loads and Time History (TH) ground acceleration motions. Dynamic TH integration is defined with linear Newmark method (β=0.25, γ=0.5) and proportional Rayleigh damping (for 1st and 2nd modes) of 1% (park or idling condition and side-to-side SS direction for operational and shutdown cases based on Valamanesh & Myers [14]) and 5% (FA direction for operational and shutdown conditions) of the critical in two orthogonal directions. At tower top is located rotor and nacelle both modelled as concentrated masses (according to centre of mass) and are connected by rigid frame elements.

Four type of towers are defined: steel tower of 90 m at hub axis (TS90), concrete tower of 120 m at hub axis (TC120), steel tower of 145 m at hub axis (TS145), and hybrid tower of 164 m to hub axis (100 m concrete section plus 62.25 m of steel section, TH164). TS90 is a common defined tower for researching purposes [7, 9, 10] provided by NREL, it is an equivalent land-based version of NREL offshore 5-MW baseline WT [13]. TS145 is a current commercial land-based tower on steel. TC120 is also a current land-based commercial concrete tower. Hybrid TH164 is a new generation of towers capable to reach a larger height as use of concrete and steel for construction. Main dimensions and properties are described in Fig. 2. All towers are simulated with the 5-MW reference wind turbine proposed by NREL [13], which is described in Table 2.

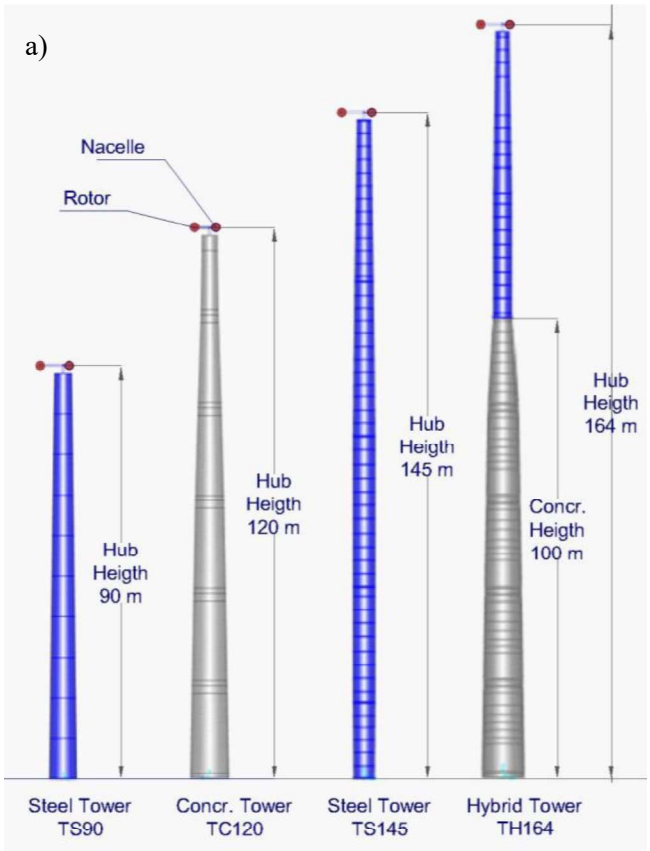
To perform analysis an integration step of 0.0025 s is used. To avoid transient effects in FAST, the seismic input has a minimum delay of 200 s, considering three initial times for EQ motion: 200 s, 250 s and 300 s.

seismic and wind loads are added directionally ± in order to obtain EQ+W envelope response. No soil-structure interaction is considered.

Table 2 –Properties for the NREL 5-MW Baseline WT [13]

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg

a)



b)

Mass and modal properties in WT

	TS90	TC120	TS145	TH164
Tower mass	347 t	1137 t	421 t	1417 t
Total mass	697 t	1487 t	771 t	1767 t
Modal Period 1st	3.1 s	3.07 s	7.69 s	4.93 s
Modal Period 2nd	0.35 s	0.59 s	0.92 s	1.14 s
Modal Period 3th	0.13 s	0.22 s	0.34 s	0.36 s
Modal Period 4th	0.07 s	0.12 s	0.18 s	0.22 s
Modal Period 5th	0.04 s	0.08 s	0.12 s	0.13 s
Modal mass 1st	72.5%	54.6%	63.3%	38.5%
Modal mass 2nd	13.7%	20.1%	14.2%	27.9%
Modal mass 3th	4.8%	8.6%	6.1%	10.5%
Modal mass 4th	2.9%	3.9%	2.8%	5.4%
Modal mass 5th	1.8%	2.6%	2.2%	3.4%
Mb Influence 1st	79.0%	68.0%	81.0%	69.0%
Mb Influence 2nd	4.0%	5.0%	5.0%	20.0%
Mb Influence 3th	8.0%	9.0%	2.0%	5.0%
Mb Influence 4th	1.0%	6.0%	5.0%	1.0%
Mb Influence 5th	0.0%	1.0%	0.0%	1.0%

Fig. 2 – (a) WT modelled with main dimensions and (b) WT mass and modal properties (with P-Delta)

It should be noted the difference in the modal participation among the 4 types of Wind Turbines (Modal mass participation). Furthermore, the modal distribution and its influence on Moment at the tower base (Mb) are different.

3. Dynamic input

3.1 Ground Motions Records

In order to incorporate seismic loads, strong ground motions were used from both horizontal components of 47 records from shallow crustal, subduction interface, and subduction intraplate sources. The time histories were corrected following Bastías & Montalva [15] and the ranges of the intensities considered within the ground motions are as follows:

PGA (g): 0.001 to 0.984

PGV (m/s): 0.004 to 3.8

Arias Intensity (m/s): 3 e^{-7} to 11.5

Cumulative absolute velocity [16] (CAV): 4.89 to 126

PSa (T=0.1s) (g): 0.106 to 3.06

PSa (T=0.5s) (g): 0.174 to 2.84

PSa (T=1s) (g): 0.076 to 2.09

PSa (T=5s) (g): 0.005 to 0.38

Mean Period (Rathje et al. [17]) (Tm, s): 0.133 to 2.12

Bracketed Duration ($D_{0.05}$, s): 2.3 to 275.9

Significant Duration ($D_{5\text{-}95}$, s): 7 to 116

These intensities represent a broad range of seismic input motions aimed at capturing not only the maximum but the dispersion of the expected responses of the wind turbines. We expect the response to be more related to the pseudo acceleration (PSa) at the first structural period or the pseudo velocity (PSv) at those periods. Also, it is expected that for design ground motion prediction models that are valid for long periods (e.g. Montalva et al. [18]; Montalva et al. [19]) will be required. While peak values such as PGA or predominant period are not well correlated to structural response of the wind turbines.

Fig. 3 shows the range of response spectra that is being using, and their power spectral density (PSD) compared to the PSD of the wind load. Note the significant difference in the frequencies affected by the ground motions and those by the wind.

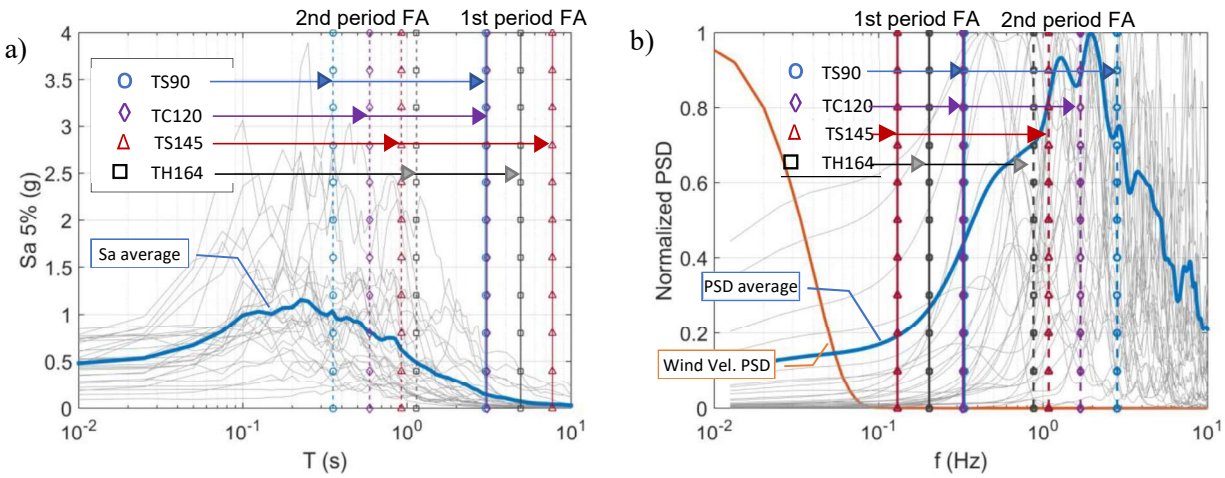


Fig. 3 – (a) Spectral acceleration Sa for EQ Ground Motion records used, and (b) Power Spectral Density PSD normalized for EQ records and wind velocity applied load

3.2 Wind Load

Wind velocities are set up to represent the range between typical average velocities of 7 m/s to 9 m/s, and the rated speed of 11.4 m/s for NREL 5-MW turbine (see Table 2), so three mean velocities are defined throw TurbSim [11] routine. Average velocity is used in IEC 2010 [3] for EQ and W combination, while recent IEC 2019 [4] proposes rated velocity to be combined. In the range of velocities described, the turbine is in operating state, and base moment increases as wind speed increases as well. Also, two wind turbulences are defined namely A and B according to IEC [3, 4]. Fig. 3b shows average power spectrum density PSD for EQ motions and wind velocity input. It can be seen, that for some cases an overlap between seismic frequency content of earthquake motion and wind velocity input occurs, e.g. Tohoku 2011.

4. Simulation Results

In order to compare coupled EQ+W and uncoupled response, basal moment (Mb) for the simulated responses is analysed. Moment is the mostly governing load, and moment at base typically defines maximum design forces for shell-tower, gate opening stress, and the foundation among others.

To validate FAST model, the towers are loaded with EQ motions without wind load. As was explained in section 2, damping is set as 1% of the critical for steel tower and 2% for concrete and hybrid towers, both in FAST and SAP2000 models when turbine is parked or idling (i.e. without W). When this condition is compared, TS90 subject to EQ with low frequency content, the validation results in good agreement as is displayed in Fig. 4a, where two peaks are highlighted at 8.225 s and 11.32 s which is near fundamental period (T_1) response. However, in cases when higher modes are considerable in dynamic response, FAST simulation not agrees with expected response. This is the case of tower TS145, where T_1 modal mass is 63% of the total. Fig. 4b exemplified that for Illapel 2015 EQ, in which case, mayor peak response at 14.85 s is highly influenced by 3th mode of T_3 = 0.36 s, while FAST can represent until 2nd mode with T_2= 1.14 s. Therefore these no-reliable cases are dismissed.

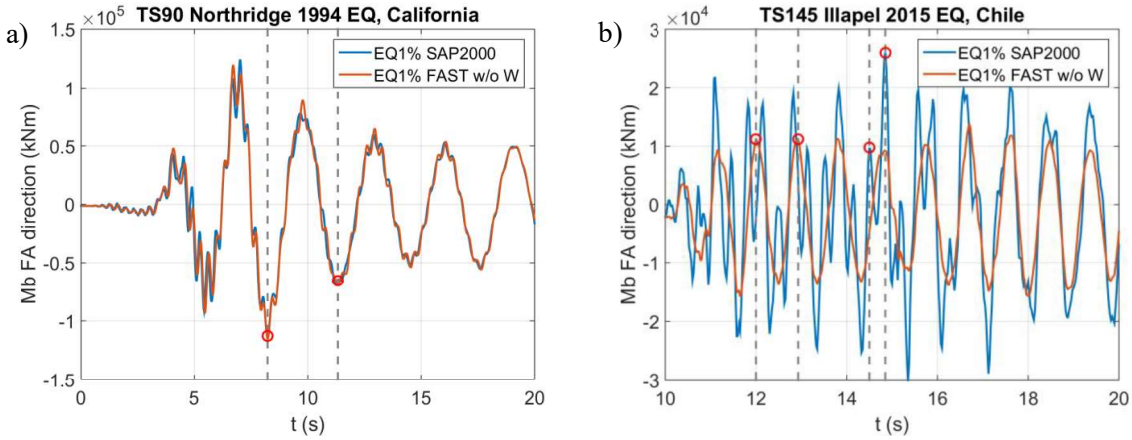


Fig. 4 – Comparison between SAP2000 and FAST Mb Response without wind: (a) TS90 Nortridge 1994 EQ, and (b) TS 145 Illapel 2015 EQ

As stated by Meng et al (8), the coupled response is highly dependent on Mb(Wind)/Mb(Earthquake) ratio (or W/EQ) especially in total damping, where higher wind velocity usually increases aerodynamic damping and therefore total damping. In Fig. 5 some TH responses obtained are displayed. In Fig. 5a a small EQ compared to W (EQ<<W) produces barely a noise in wind load basal moment for TS145. However, Fig. 5b shows that for W/EQ = 2.3, EQ load is important enough to influence in coupled response. In this case, coupled response = 8.71E4 kNm, and at the same time step uncoupled = 8.22E4 kNm composed by 31% EQ

plus 69% W. It can be noticed that uncoupled > coupled response, this occurs in some simulations, and can be explained partly because of differences between imposed 5% damping in FA direction for SAP2000 FEM, and effective structural plus aerodynamic damping calculated by FAST in coupled analysis, which not necessarily matches 5% damping [8].

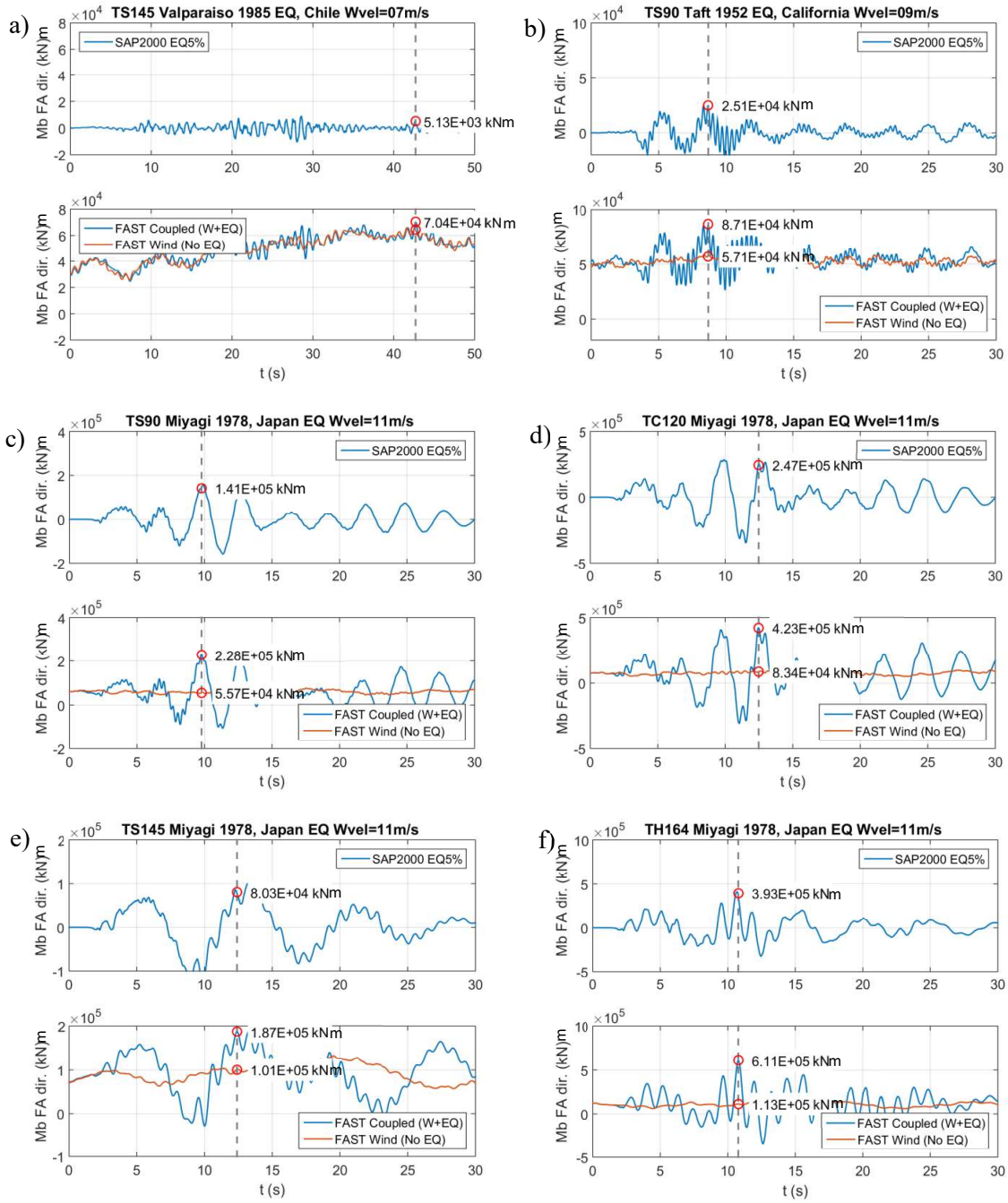


Fig. 5 – Time-history results for coupled (EQ+W) and uncoupled response in operation OP

When EQ is considerably greater than W (EQ >> W), as for Miyagi 1978 record, the basal responses seems to be less affected by aerodynamic damping, but offset, increasing response for some towers. For TS90 WT

(see Fig. 5c) coupled response = 2.25E5 kNm and uncoupled = 1.97E5 kNm (71.6%EQ +28.4%W), while TS145 (Fig. 5e) coupled response = 1.87E5 kNm and uncoupled =1.81E5 kNm (42.8%EQ+57.6%W). Concrete tower TC120 (Fig. 5d) coupled response = 4.23E5kNm and uncoupled = 3.30E5kNm (74.8%EQ+25.2%W), then coupled response is much greater than uncoupled. Finally, hybrid tower TH164 (Fig. 5f) coupled response = 6.11E5kNm and uncoupled = 5.06 (77.7%EQ+22.3%W), again coupled response much greater. This analysis is not simple, because of horizontal orthogonal combination, and EQ, W and coupled maximum response should not be coincident in time. This discussion is part of the next section.

Emergency shutdown is also simulated (SHD). As turbine is equipped with monitoring sensors, in case of earthquake motion these devices can activate brake system. In most of the cases, shutdown loads overcome operating loads. Although many times shutdown produces only a limited increase compared to operational response, it could become particularly important in some case and must be included in wind turbine analysis. Two cases for Northridge 1994 EQ are presented in Fig 6.

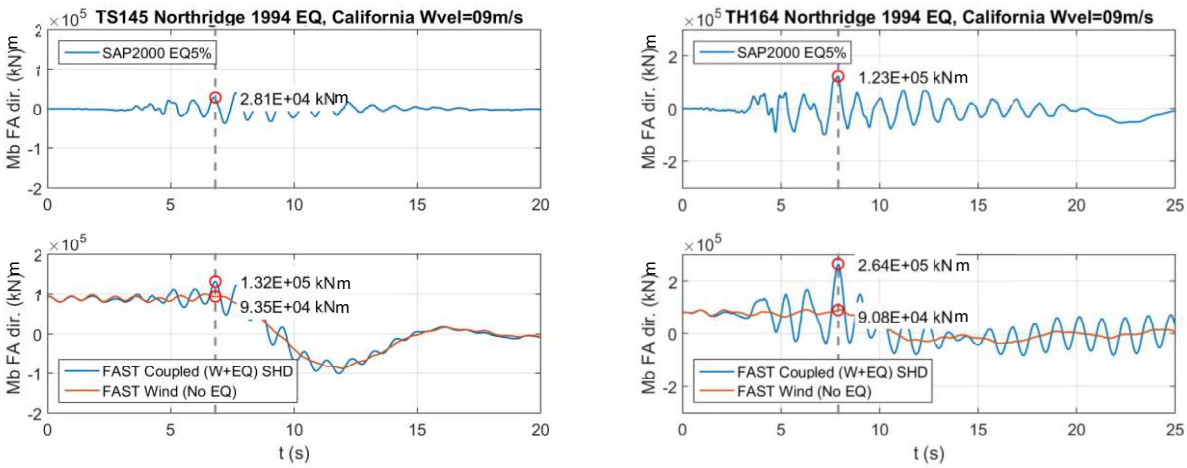


Fig. 6 – Time-history results for coupled (EQ+W) and uncoupled response for SHD response

5. Result Analysis

As was explained in previous section, maximum base moment obtained from coupled FAST simulation (EQ+W) and uncoupled FAST (W) and SAP2000 (EQ 5% damping in FA direction and 1% damping in SS direction) simulations are studied. Uncoupled simulations are combined in the classical ways already mentioned: direct sum = EQ+W, 0.75·direct sum = 0.75·(EQ+W) and SRSS = $\sqrt{(EQ^2+W^2)}$. Besides, as a way to consider EQ unaffected by W, additional a weighted combination sum of EQ+a·W is studied.

Fig. 7 displays coupled and combined maximum base moment response, grouped by towers and combination rules. In this way, the 1:1 line (in black) split conservative and non-conservative results, i.e. if combination of uncoupled responses results in equal, higher or lower value compared to expected coupled response. Direct sum (Fig. 7a) is, as expected, very conservative for TS90, TS145 and TC120, and somewhat conservative for TH164. Coefficient 0.75 (Fig. 7b) applied to EQ+W is non-conservative, at least for most of the cases analysed in this paper. SRSS superposition (Fig. 7c) shows reasonable agreement for towers TS90 (as is concluded by other authors [7, 8]), however underestimates coupled response for taller towers as TS145 and TH164. Finally, weighted combination EQ+a·W, where a=0.85 according to setting from Fig. 7d, seems to be a reasonable approach for TS90, TC120, TS145, andTH164 hybrid tower.

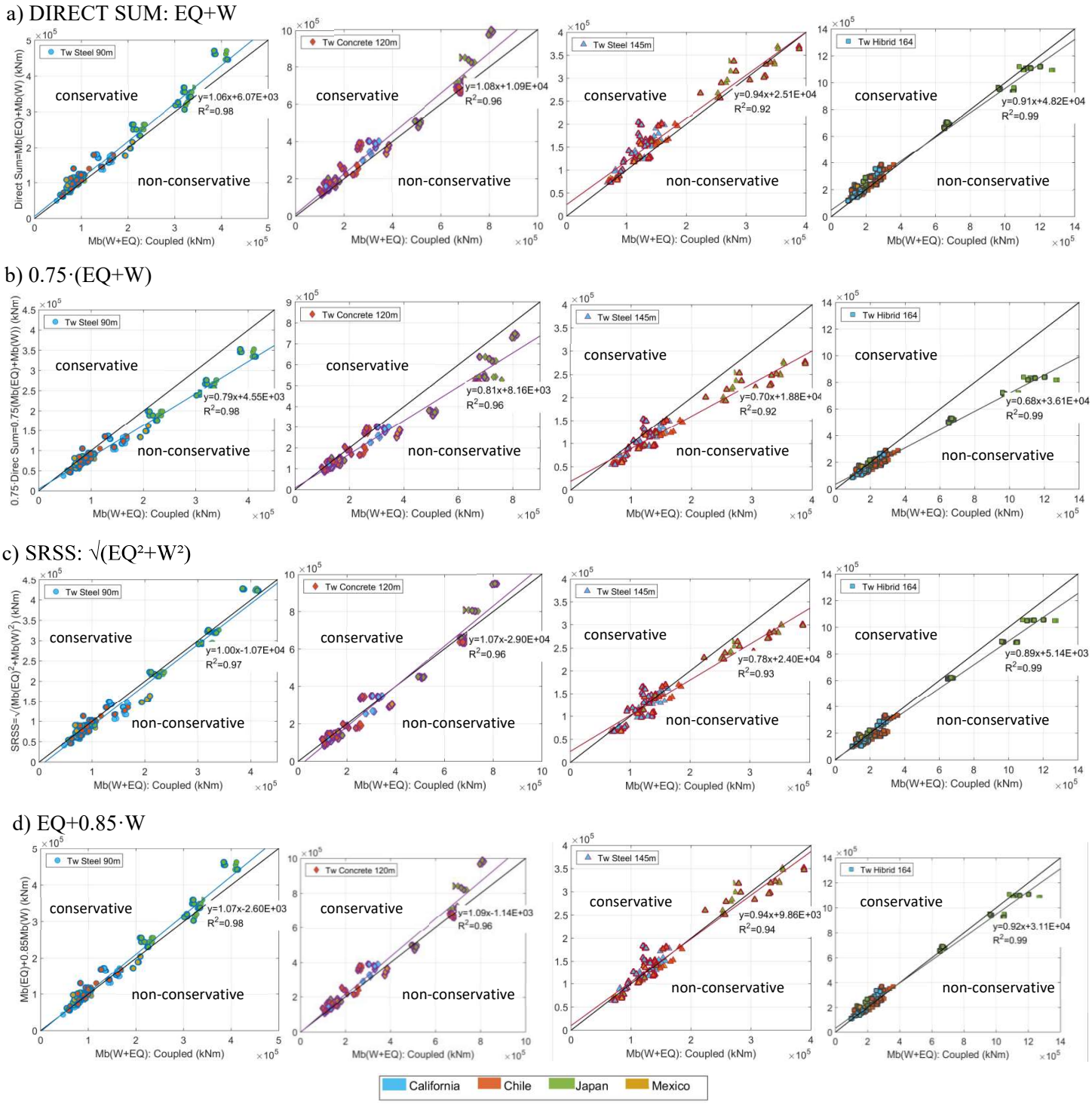


Fig. 7 – Maximum Mb coupled and combined (uncoupled) grouped by tower and combination rule approach. Filler colour of marker indicates EQ region

In order to analyse efficiency for load combination approaches, wind over seismic load ratio (W/EQ) is studied. In Fig. 8a four combinations are shown; notice that results > 1 are conservative for design and non-conservative otherwise. It is observed important dispersion on data, which can be improve by clustering

them. One of the well-known intensity measures is the acceleration spectral ordinate for T_1 (Sa T_1) as presented in Fig. 8b. For TS90 the results are consistent with reported in previous works [7] nevertheless hybrid tower does not reasonable match. This is expectable as TH164 does not have its mass concentrate in fundamental mode, but distributed at least in the first three or four modes. This behavior cannot be ignored.

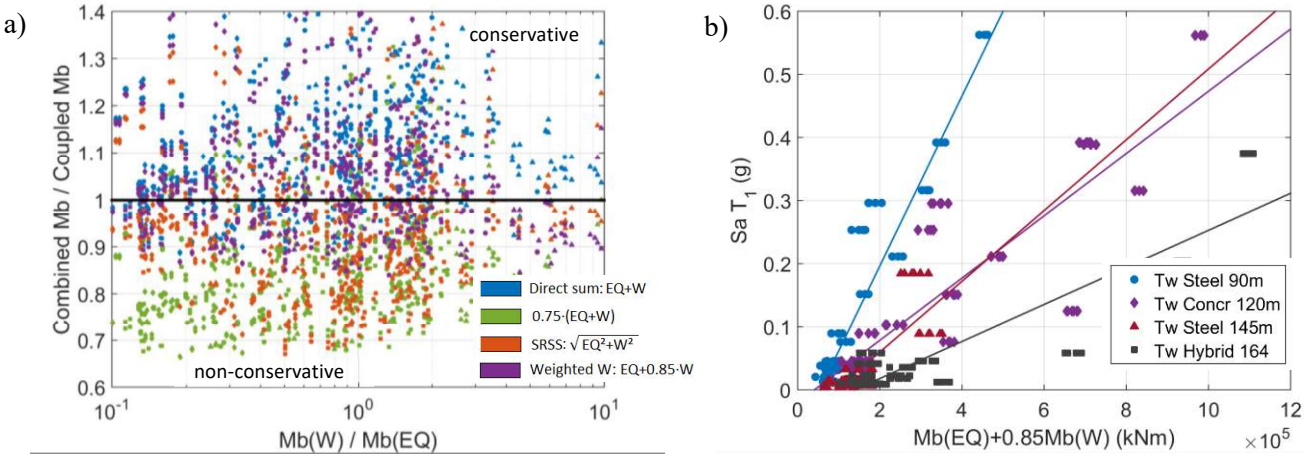


Fig. 8 –W/EQ ratio (a) and fundamental period spectral ordinate (b) comparison

6. Conclusions

This paper presents coupled analyses simulations between aerodynamic and seismic loads of wind turbines in order to propose combinations rules when both actions are considered in an uncoupled way, which is the state of practice of the industry. The analyses have been performed using FAST software [11]. Four types of WT have been used with fundamental periods ranging from 3.1 to 7.7 s, and which dynamic behaviours are different (fundamental period and modal participation). Also, different seismic sources have been considered into the analysis (shallow crustal, subduction interface and subduction intraplate) who are representative of the wide range of seismic scenarios where these WT are located (USA, Japan, Chile, Mexico, etc.).

The results show that for the TS90 wind turbine (H=90 m, T_1=3.1 sec), SRSS combination rule of aerodynamics and seismic uncoupled loads has a reasonable agreement with their coupled response, which is similar to values reported in previous studies [7, 8]. For TC120 WT (H=120, T1=3.07 s), TS145 WT (H=145 m, T_1=7.7 sec) a better matching is reached with the proposed combination rule: EQ + 0.85W. Finally, for TH164 WT (H=164 m, T1=4.9 sec), results show that the following combination rules could be reasonable: direct sum EQ+W or EQ+0.85W. Nevertheless, for TH164 WT, coupled simulations using FAST would not be accurate enough, which is because of this software does not take into account 3rd and 4rd modes of the WT dynamic response, therefore additional research is needed in order to found the best combination rule

It should be noticed that the combination rule from ASCE/AWEA RP2011 [5], i.e. 0.75·(EQ+W), at least in most of the cases analyzed, tend to underestimate the coupled response. Therefore, the Authors do not recommend consider this approach in new generation WT located in high seismic regions.

Finally, it is important to mention that our results show that the combination rule of aerodynamic and seismic uncoupled loads depends on several factors such as: fundamental period of WT, modal participation of higher modes, damping and seismic-tectonic source (frequency content) among others.

A Probabilistic approach for the combination rules of aerodynamics and seismic loads should be considered in futures studies.

7. Authors independence declaration

The authors declare that they have no financial interests or personal relationships with vendors of Wind Turbines that could influence the work reported in this paper.

8. Acknowledgements

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