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RESPONSE OF A SMALL WIND TURBINE TOWER UNDER EARTHQUAKE LOADS

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Abstract

As the concern with the environment and the economical aspect of the use of fossil energies grows, the studies and application of renewable energy systems also increase. Wind energy is an important renewable energy system that can be used on a large or small scale. Indeed, the small-scale systems, known as small wind turbines (SMT) are used as an attractive solution to solve energy problems in rural or difficult access areas, that can be affected by seismic forces. The present paper analyses the seismic response of metallic tower used as a support for a SWT submitted to modal response spectrum method (MRSA) and response history analysis (RHA). The analyses were performed with the elastic response spectrum function given by Portuguese Annex to Eurocode 8, while the time history used the accelerations records of El Centro Earthquake scaled to match the elastic response spectrum

The results suggest that the beam model is appropriate for studying the seismic response of the tower, although it has some limitations. The horizontal accelerations at the ground surface were amplified by a factor of 6 at the top of the tower, but the displacements were not significant. However, the base reactions for a strong ground motion could be compared to those obtained by the wind forces that the tower and wind turbine experience.

The MRSA base responses were 30 to 40% lower than those obtained by RHA. For the northern region of Portugal, far-fault type led to higher responses than the near-fault. Overall, this study provides valuable insights into the seismic behavior of small wind turbines and highlights the importance of accounting for seismic loads in their design and construction to ensure their structural safety and stability.

Keywords: small wind turbine, metallic tower, dynamic responses, finite element analysis, seismic analysis, Eurocode 8.

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1 INTRODUCTION

The events that occurred at the outset of 2022 highlight the significance of Europe's energy independence, with the potential for advancements in the renewable energy sector to grow even further in the upcoming years. Notwithstanding, research in the wind energy domain has typically focused on large, on-grid wind turbines, with little attention given to the potential of small wind turbines (SWT) for off-grid utilization in rural or remote areas.

While wind-driven forces are widely considered as the primary hazard for wind turbines, earthquakes are not typically regarded as a significant concern for large wind turbines due to their vibration period ranging from 1.5 to 12 seconds, which corresponds to the low-intensity portion of seismic events [1-5]. When compared to shorter-period structures, the long vibration period of large wind turbine support structures allows them to absorb some of the energy from earthquakes, lowering the force and impact on the structure. this statement might not apply to small wind turbines (SWT) since they have a shorter natural vibration period than their larger counterparts due to their smaller rotor diameters and lower tower heights. Furthermore, the cantilever design of SWT structures exacerbates their susceptibility to earthquake excitation.

Current guidelines, such as Risø [6], GL [7], and IEC [8], recommend that seismic design must comply with seismic loading requirements outlined in design building code of the installation site. Unlike building projects, in which structures must develop inelastic deformation in response to seismic activity, for wind turbines, the objective is to minimize operation interruption, thus verifying service limit state parameters, i.e damage limitation [6].

Seismic evaluation of structures can be conducted using three methods: simplified, modal response spectrum analysis (MRSA), or response history analysis (RHA). In the Eurocode 8 [9], the simplified method, also known as the static load method, employs static loads to estimate the structural response to earthquake forces, but should only be employed for structures that meet the standard requirements. The MRSA method employs structural natural frequencies and corresponding mode shapes to calculate the response of a structure to earthquake forces based on the spectral acceleration, which is useful and widely used. However, this method has some limitations, such as assumptions of linear behavior, limited accuracy for irregular structures and high-frequency content, lack of consideration of soil-structure interaction, and limited applicability to non-building structures. On the other hand, RHA is a complex method that analyzes the dynamic behavior of a structure under earthquake forces based on the actual recorded or synthesized ground motion time history. It considers the nonlinear behavior of the structure and provides detailed information on the structural response. However, due to its complexity, it is computationally intensive [10].

The present study aims to analyze a metallic tapered tower utilized as a support for an SWT subjected to strong ground motion in accordance with seismic specifications for the North region of Portugal, where the real structure is installed, characterized by the El Centro earthquake. The MRSA method was employed using the response spectrum in accordance with Eurocode 8, while the same spectrum was used to scale the El Centro earthquake time history used in the RHA method.

2 DESCRIPTION OF THE TOWER

The School of Technology and Management of the Polytechnic Institute of Bragança in Portugal houses a 17.8 m tall metal tower constructed from steel S275. The tower has a hexadecagonal section, with an outside diameter of 0.5890 m at the base and 0.1954 m at the top, and a constant wall thickness of 4 mm. The tower is securely fastened to a gravity-based foundation by 16 anchor bolts attached to a flange at the base. Further details regarding the key properties of the tower can be found in Table 1.

Density	7850.000	[kg/m³]
Young's modulus	210.000	[GPa]
Poisson's ratio	0.300	--
Yield strength	275.000	[MPa]
Height	17.800	[m]
Top diameter	0.195	[m]
Bottom diameter	0.589	[m]
Nacelle mass	75.000	[kg]
Tower mass	664.277	[kg]

Table 1: Tower properties.

In this study, the wind turbine tower is represented as a multi-degree of freedom system, with the rotor and nacelle masses being modeled as a lumped mass located at the hub height. Two distinct models were evaluated using the SAP2000 software: a beam model and a more sophisticated shell model. To ensure the accuracy of the models, they were validated against experimental results obtained from Experimental and Operational Modal Analysis [11].

2.1 Modal Response Spectrum analysis (MRSA)

To perform Modal Response Spectrum Analysis, an elastic response spectrum function was constructed according to the EN 1998-1-1:2004 Section 3.2.2.5 [9], taking into account the Portugal national Annex specifications and the site location. The north region of Portugal is categorized as a low seismic region with a seismic zone of 1.6 for far-fault actions and 2.5 for near-fault actions, both having the lowest ground acceleration reference, a_{gR}, as shown in Table 2. Soil type is another crucial factor that needs consideration in seismic evaluations, even when not accounting for specific soil-structure interaction in fixed base. For this analysis, soil type D was chosen, which comprises soils with low shear strength, such as loose sands and silts, and soils with high plasticity, such as clayey soils [9].

Seismic Zone	**1.6**	**2.5**
$a_{gR}[\ m/s^2]$	0.35	0.8
class IV- γ_I	1.95	1.5
Soil type D – Smax	2.0	2.0

Table 2: Seismic parameters.

Wind turbines have traditionally been considered structures of low importance and have been assigned to the lowest importance class (Importance Class II) in Eurocode 8. However, given the growing global reliance on wind energy and the increasing role of wind turbines as critical infrastructure, there is a need to reconsider the importance class assigned to these structures [1]. In this study, the importance class of a wind turbine structure was reassigned to Class IV, taking into account its vital role in maintaining operational civil protection services, as prescribed by Eurocode 8-6 [12].

The uniaxial analysis of the models was carried out to enable a comparison between the MRSA and RSA methods. The modal analysis involved the use of load-dependent Ritz vectors with a modal participation factor of up to 90%, consistent with the recommendations set out in Eurocode 8. In order to achieve this level of modal participation factor in both x and y directions, 16 modes were considered for the shell-type model and 12 modes for the beam model.

The expected maximum seismic load was determined by combining the respective modal responses using the Complete Quadratic Combination (CQC) method as detailed in [13, 14]. The design response spectrum was then evaluated for accuracy and reliability through comparison with time series analysis.

2.2 Response History Analysis (RHA)

The time history analysis was performed using the time series accelerations presented in Figure 2 from the El Centro Earthquake, which occurred in Southern California on May 18, 1940. This earthquake had a magnitude of 6.9 on the Richter scale and a peak ground acceleration (PGA) of 0.289g. The El Centro Earthquake is frequently used as an acceleration signal for seismic analysis due to its well-documented characteristics and its status as a benchmark earthquake.

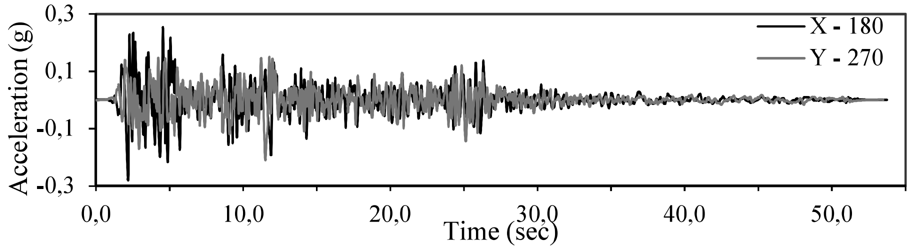

Figure 1 : Imperial Valley-06 1979, El Centro Array #4 time-history accelerations

In this study, the aim was to compare the results of time history response with those of response spectra analysis. In order to accomplish this, it was necessary to scale the time series accelerations to conform to the response spectrum. The response spectra were matched using the Frequency Domain Method, which preserves the Fourier phase of the reference time history while adjusting the Fourier amplitude spectrum to match the target response spectrum. The matched response spectra for both types of seismic action and directions are show in Figure 3.

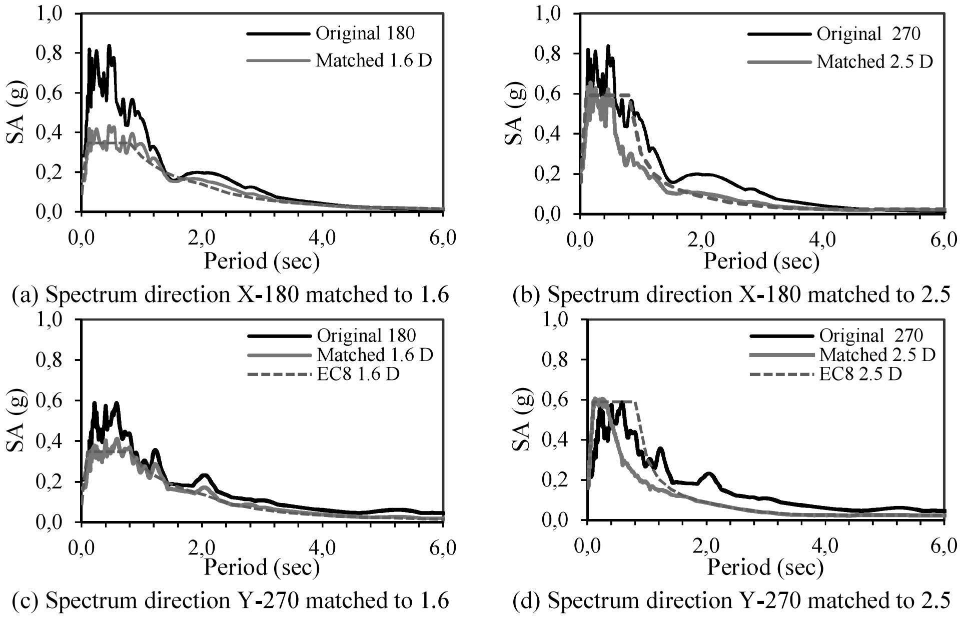

Figure 2 : Response spectrum functions

3 RESULTS

The analysis of the structure using the Finite Element Method (FEM) is performed using the SAP2000 Software, modal analysis was conducted to validate the models used in the study. The results of the analysis are presented in Table 2, which indicates that both models show good agreement with the experimental results [11].

In modern structural analysis, the lowest modes of vibration are often considered sufficient to meet the requirement of a 90% participation factor. However, relying solely on the lowest modes may not provide a complete understanding of the dynamic behavior of a structure. Higher modes can significantly contribute to the overall response of the structure, and their inclusion in the analysis can lead to a more accurate representation of the structural response under seismic loads. In the current analysis higher modes are needed to achieve at least 90% participation factor in each direction.

	Shell		**Beam**		**Experimental [11]**
Mode	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)	
1	0.625	1.600	0.621	1.611	1.55±0.05
2	0.625	1.601	0.621	1.611	1.55±0.05
3	0.142	7.043	0.142	7.066	5.8 ±0.05
4	0.142	7.045	0.142	7.066	5.8 ±0.05
5	0.054	18.414	0.054	18.466	18.16 ±0.05
6	0.054	18.421	0.054	18.466	18.16 ±0.05
7	0.028	35.885	0.028	35.988	
8	0.028	35.898	0.028	35.988	
9	0.017	59.208	0.017	60.512	61.65 ± 0.05
10	0.017	59.229	0.017	60.512	61.65 ± 0.05
11	0.011	88.225			87.6 ± 0.05
12	0.011	88.255			87.6 ± 0.05
13	0.008	131.055	0.008	123.046	
14	0.008	131.089	0.008	123.046	
15	0.004	269.802			
16	0.004	270.105			

Table 3: Modal frequencies.

The seismic analysis results for the tower using both shell and beam models are tabulated in Table 3. The comparison of the results indicates that both models demonstrate comparable behavior. However, the beam model exhibits slightly higher peak ground acceleration (PGA) values while the displacements are marginally lower for the TH ElCentro and TH 1.6 D in the X direction. These observations suggest that the beam model is suitable for seismic analysis of the tower up to a certain extent. It is important to note that buckling analysis was not evaluated in this study, and therefore, the suitability of the beam model may vary in the presence of buckling effects.

Furthermore, the maximum displacement observed for the Y-270 component of the El Centro earthquake was found to be 91.393 mm. This result highlights the importance of accounting for seismic loads in the design and construction of tall structures, as these displacements can cause significant damage and compromise the integrity of the tower. Overall, the results demonstrate the effectiveness of the seismic analysis approach adopted in this study, and the suitability of the beam model for analyzing the seismic behavior of the tower.

	Dir.	Ground PGA [m/s^2]	Top PGA [m/s^2]		Amplification	Displacement [mm]	
			Beam	Shell		Beam	Shell
TH ElCentro	X	2.80	13.211	13.127	4.7	82.230	84.578
TH 1.6 D	X	1.50	7.163	7.145	4.8	53.873	55.530
TH 2.5 D	X	2.20	10.220	10.114	4.6	57.080	56.992
EC8 1.6 D	X		5.584	5.585		49.037	49.654
EC8 2.5 D	X		5.904	5.894		41.022	41.344
TH ElCentro	Y	2.10	11.075	10.228	5.3	91.393	84.183
TH 1.6 D	Y	1.64	7.724	7.166	4.7	65.319	60.896
TH 2.5 D	Y	1.99	9.873	9.303	5.0	61.571	56.360

Table 4: Comparisons accelerations and displacements responses.

The seismic analysis of the tower presented in this study provides valuable insights into the dynamic behavior of the structure under seismic loads. The maximum displacement of 91.393 mm observed for the Y-270 component of the El Centro earthquake indicates that the tower has the ability to withstand seismic events of similar intensity. Moreover, the displacement values obtained from MRSA and RSA analyses, which were matched to Eurocode spectrum for both far-fault and near-fault, were found to be within the allowable limit of 89 mm, as required by Eurocode 8-6 for damage limitation. These findings suggest that the tower is adequately designed to resist seismic loads.

Additionally, the analysis using EC8 showed that seismic displacements are not a SLS concern, as wind action leads to larger displacements around 200 mm [15]. The top of the tower was found to exhibit the maximum amplification of accelerations, with both the beam and shell models exhibiting an amplification factor of approximately 5 for both horizontal components. This was observed through the analysis of various time histories, with Figure 1 showcasing the amplification in the X-180 component. Similar behavior was observed in other time histories.

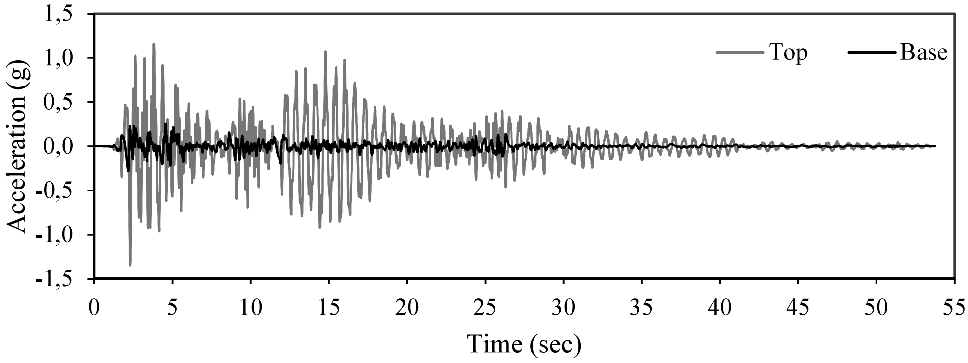

Figure 4: Base and top accelerations X-180 direction component of El Centro earthquake

Although the displacements are not a concern for this structure, it is still necessary to check the shear base forces and moments. Table 5 summarizes the base reaction forces obtained from the seismic analysis. A detailed examination of the table reveals that the seismic actions can produce shear forces and overturning moments that are comparable to those induced by wind forces [15]. Therefore, the design should consider both the seismic and wind loads to ensure the structural safety and stability.

Analysis	Direction	F [kN]	M [kN.m]
TH ElCentro	X	3.017	32.368
TH 1.6 D	X	1.801	19.736
TH 2.5 D	X	1.995	21.340
EC8 1.6 D	X	1.345	17.432
EC8 2.5 D	X	1.423	15.288
TH ElCentro	Y	2.794	33.480
TH 1.6 D	Y	2.099	24.506
TH 2.5 D	Y	1.985	22.859

Table 5: Base reaction forces beam type.

Research has shown that the base shear force and overturning bending moment calculated via time-history analysis were larger than those obtained from the elastic response spectrum analysis. Specifically, the time histories TH 1.6D and TH 2.5D in the Y-270 direction resulted in moments that were 41% and 50% higher than those from MRSA EC8 1.6D and 2.5D.

It is interesting to note that the unscaled El Centro time-history response generated overturning moments that were 64% higher than the matched time history for seismic zone 2.5D in the X-direction and only 36% higher for seismic zone 1.6D in the Y-direction.

Overall, the research revealed that the far-fault excitation (1.6) resulted in higher responses than the near-fault (2.5). Figure 5 shows that the far type's frequency content is closest to the lower modes than the near types. It is noteworthy since if the frequency content of the time history is close to the structure's natural frequency, the structure's response can indeed be substantially amplified.

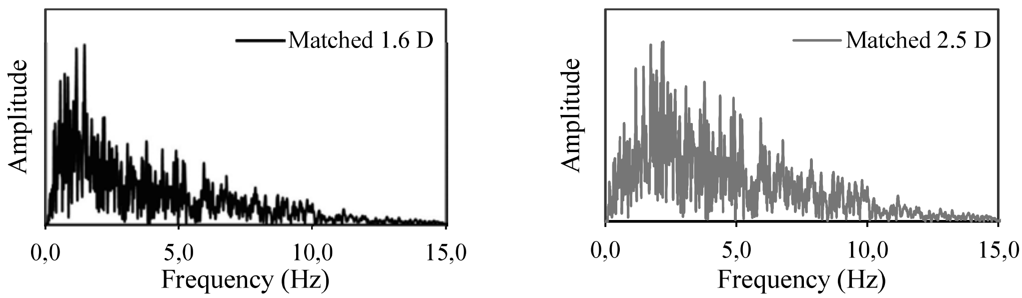

Figure 5: Frequency content of X-180 direction component of El Centro earthquake matched to seismic zone 1.6 and 2.5

4 CONCLUSIONS

The seismic response of a small wind turbine tower was analyzed by finite element models (beam and shell), for modal response spectrum analysis using the elastic response spectrum function in accordance with Eurocode 8, and respective Portuguese annex and a time history analysis corresponding to the El Centro earthquake with the time histories matched to elastic response function used in MRSA.

The results of the seismic analysis for the tower using both shell and beam models demonstrated comparable behavior. However, the beam model exhibited slightly higher PGA values, while the displacements were marginally lower for certain earthquake components in the X direction. These observations suggest that the beam model is suitable for seismic analysis of the tower up to a certain extent, but the suitability may vary in the presence of buckling effects.

The analysis using showed that the displacement values obtained by MSRA and corresponding matched time histories were within the allowable limit of 89 mm, as required by Eurocode 8-6 for damage limitation. This suggests that the tower is adequately designed to resist seismic loads. However, it is still necessary to check the shear base forces and moments as seismic actions can produce shear forces and overturning moments that are comparable to those induced by wind forces.

The research also showed that the base shear force and overturning bending moment calculated via time-history analysis were larger than those obtained from the elastic response spectrum analysis. Moreover, the far-fault excitation (1.6) resulted in higher responses than the near-fault (2.5), with the frequency content of the far type closest to the lower modes than the near types. This indicates that if the frequency content of the time history is close to the structure's natural frequency, the structure's response could be substantially amplified.

In conclusion, the seismic analysis approach adopted in this study was effective in providing valuable insights into the dynamic behavior of the structure under seismic loads. The results demonstrate the suitability of the beam model for analyzing the seismic behavior of the tower and highlight the importance of accounting for seismic loads in the design and construction of small wind turbines towers to ensure structural safety and stability, even in areas with low to moderate seismic activity.

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