Nondeterministic dynamic analysis and fatigue assessment of wind turbine towers

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Abstract. Wind energy has been playing a very important role in whole world energy matrix. In this sense, a great technological evolution has occurred over several decades, transforming old windmills into extremely tall and slender towers, with the capacity to generate large amounts of energy. In Brazil, considering this advance, the conventional conical steel tower is a predominant type of supporting structure. According to this context, this research works aims to study the dynamic structural response and structural fatigue assessment (service life) of a steel tower to support a wind turbine model MM92 by Repower. In this way, a numerical model was developed to represent the investigated tower, using the Finite Element Method (FEM) simulations implemented in the ANSYS program. The analysis of the non-deterministic dynamic response of the tower is performed for several wind velocities, having in mind a critical evaluation about the maximum values obtained for the von Mises's stresses and the service life of the investigated structure. Finally, the results obtained along this research work are evaluated and compared with the limit values recommended by international design codes and recommendations.

Keywords: Steel wind tower, non-deterministic wind dynamic loads, numerical modelling, fatigue verification.

1 Introduction

The growing demand for energy in conjunction with technological development, and the quest to obtain pure energy without causing major impacts on the environment, stimulated the development of systems capable of capturing energy from renewable sources, such as wind, tide and the sun. Wind energy has seen great developments in recent decades, transforming small windmills from centuries ago into slender steel towers with the capacity to generate large amounts of energy [1]. Considering that of the slenderness of these new structural models, it's necessary and extremely important to study their dynamic non-deterministic structural behavior, since these towers face even greater wind loads due to their increasing height.

This study investigates the dynamic structural response of a conic steel tower with 76.15 meter high, used to support a model MM92 wind turbine form Repower [2], when subjected to non-deterministic wind loads considering velocities of 10 m/s [36 km/h] to 70 m/s [252 km/h]. In this investigation, the loads associated to the structure's weight, the forces generated by the rotor, and the effect caused by the release of vortices was considered in the tower dynamic analysis.

The developed wind turbine tower finite element model considered the soil-structure interaction effect when the dynamic response was investigated. The results are presented based on the maximum translational horizontal displacements and von Mises stresses. Considering the maximum stresses on the structure, the steel tower's service life was determined following the classic methodology for fatigue damage assessment, based on the use of S-N curves and the Palmgren-Miner linear damage rule [1]. Finally, the maximum displacements and stresses were compared with limiting values recommended by current design standards.

2 Investigated structural model

The investigated structural model is a conical steel tower to support a wind turbine model MM92 by Repower [2]. Its production range is from wind velocities of 3 m/s to 24 m/s. The tower is 76.15 meters high and was divided into three parts for logistical reasons, as shown in Fig. 1. The foundation is an octagonal shoe inscribed in a circumference of 17 m in diameter and with a constant height of 2.5 m, as show in Fig. 1.

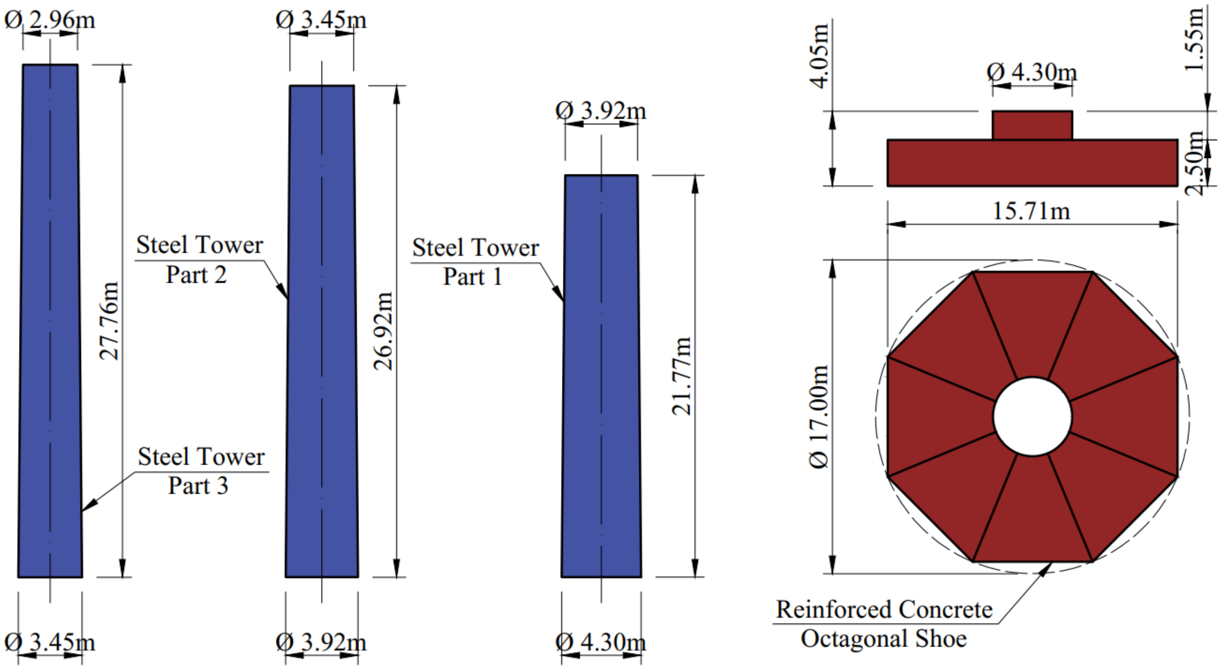


Figure 1. Geometric features of the steel tower and foundation

The parts of the tower are interconnected with each other by flanges and screws. In its first part, there are two openings, one used to access its interior and another for ventilation, both in the shape of an ellipse and have stiffeners to compensate for the loss of material. The steel tower, including all its components, is manufactured in S355 steel, with yield strength of 355 MPa. The octagonal shoe is composed of reinforced concrete with fck equal 16 MPa.

3 Finite element modelling of the wind turbine tower

The developed finite element model presents an appropriate degree of refinement, allowing for a good representation of the dynamic structural behaviour of the investigated wind turbine tower. In this model, the nacelle, rotor and propellers were represented by a shell element with a density equivalent to their respective masses. The model presents 72.399 elements, 43.339 nodes and 160.764 degrees of freedom.

In this research work, the finite element SHELL 181 [3] was used for represent the steel tower and nacelle; the three-dimensional element SOLID 72 [3] was utilised to simulate the reinforced concrete octagonal foundation; and the spring element COMBIN 39 [3] was used to consider the soil-structure interaction effect. This way, the representation of the soil stiffness was adopted based on the soil elastic modulus, and considering the subgrade reaction coefficient defined according to Oliveira [4]. In order to correctly represent the interaction between the steel tower and the reinforced concrete foundation, it was necessary to properly connect the nodes of the tower shell elements SHELL 181 [3] with those associated to the foundation (SOLID 72 [3]). Figure 2 presents the numerical model developed to the dynamic structural analysis and fatigue analysis of the investigated wind turbine tower.

Nodes: 43.399 **Elements:** 72.399 **Degrees of freedom:** 160.764

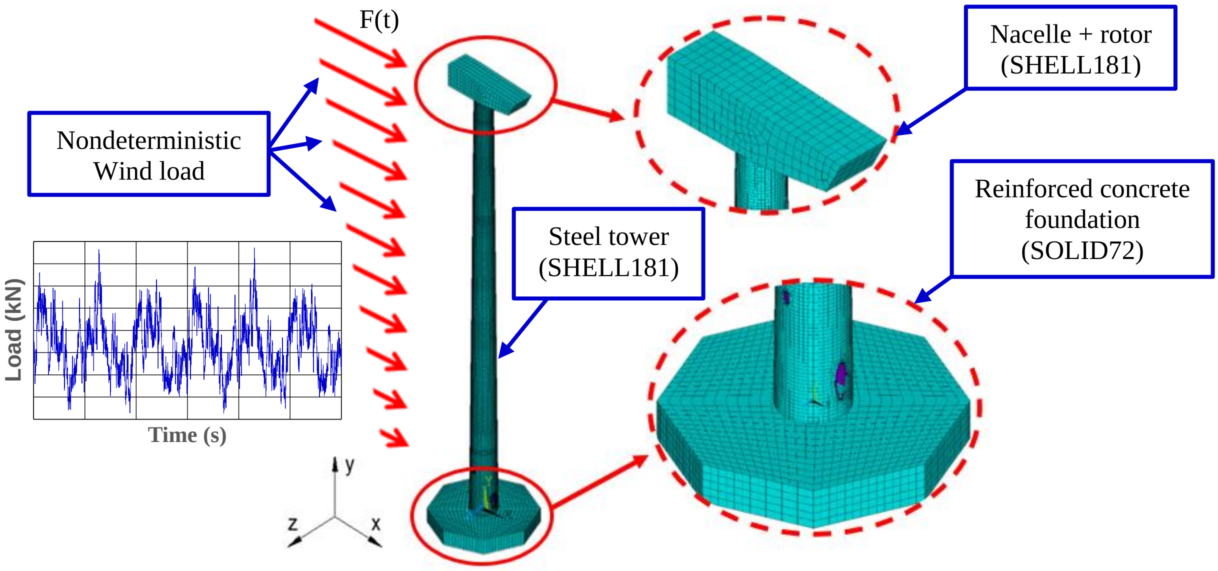


Figure 2. Finite element model of the wind turbine tower [1].

4 Non-deterministic wind load model

Wind is a phenomenon of random and unstable character, with an inadequate deterministic consideration for its simulation. However, some hypotheses can be considered for the simulation of these loads, the wind flow is unidirectional, stationary, and homogeneous. This implies that the direction of the wind flow is constant in time and space; its characteristics do not change during the simulation. For your simulation, it is necessary to generate functions over time that concern the floating part of the wind, these functions can be generated though a Fourier series using a power spectrum. In this study, the Kaimal power spectrum was used, as it considers the height "z" to determine the spectral density of the wind, as show in Fig. 3.

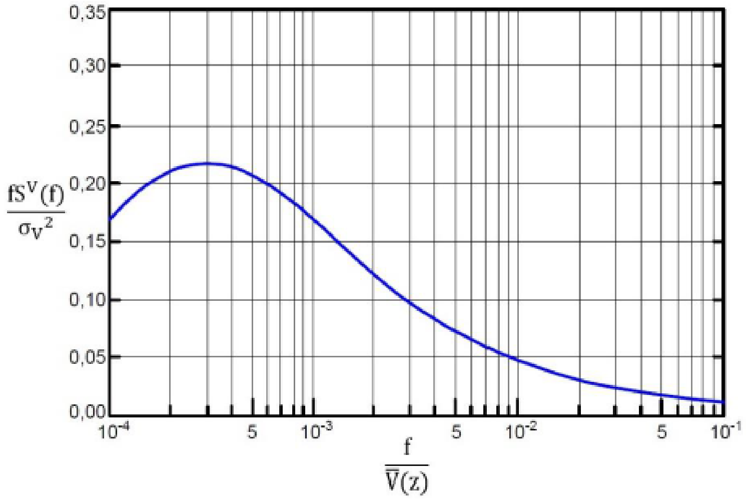


Figure 3. Kaimal wind power spectrum [4].

Based on a single harmonic function, the floating portion of the wind can be represented, this plot is related to the stationary random process with an average of zero, considering the superposition of the harmonic waves, the fluctuations are expressed and the amplitudes of the functions in the time domain [4]. The dynamic wind load over time at each node in the tower is expressed by Eq. (1), where C_{ai} is the drag coefficient in region i, q(t) the dynamic wind pressure and at last A_i is the frontal area of the contact surface.

$$F(t) = C_{ai}\, q(t) A_i \tag{1}$$

With the Kaimal spectrum, a wind power spectrum density function, the amplitude of each harmonic can be obtained. The power spectrum is given by Eq. (2) and (3) and the friction velocity is determined by Eq. (4). Where f represents the frequency, $S^v(f)$ is the wind spectral energy density in the frequency f, x is the dimensionless frequency, V_y is the velocity at height z, k is the Karman constant, u_* is the friction velocity related to the wind power spectrum density and y_0 is the roughness length.

$$\frac{fS^V(f,y)}{u_*^2}=\frac{200x}{(1+50x)^{5/3}} \tag{2}$$

$$x(f,y)=\frac{fy}{V_y} \tag{3}$$

$$u_*=\frac{k\overline{V_y}}{\ln(y/y_0)} \tag{4}$$

Assuming that the floating portion of the wind is associated with the stationary random process with an average equal to zero and considering a superposition of harmonic waves, the floating portion can be expressed as in Eq. (5). Where N is the total number of frequency increments, S^V is the wind spectral energy density of the floating part of the wind velocity, f_i is the frequency in Hz, Δf is the frequency increments in the interval [f_{min}, f_{max}], θ_i is the random phase angle normally distributed in the interval [0-2π] and t is the time in seconds.

$$v(t)=\sum_{i=1}^{N}\sqrt{2S^V(f_i)\Delta f}\cos(2\pi f_i t+\theta_i) \tag{5}$$

In this study, it was assumed that the pressures acting on the structural system are calculated directly as a function of velocity (Davenport's classical model) [4]. To obtain the results, is considered the wind acting on the structure during a time interval of ten minutes (six hundred seconds). Figure 4 shows the wind load acting on the structure at the top of the wind tower at velocities of: 20 m/s [72 km/h], 35 m/s [126 km/h] and 50 m/s [180 km/h].

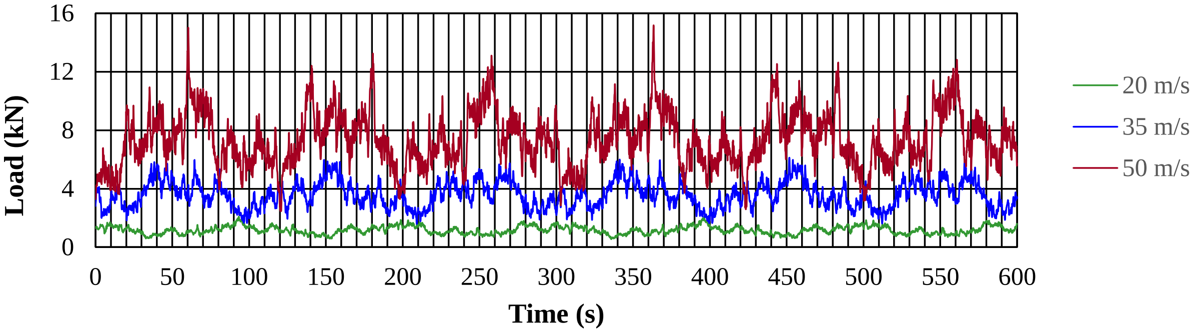


Figure 4. Non-deterministic dynamic forces in the time domain.

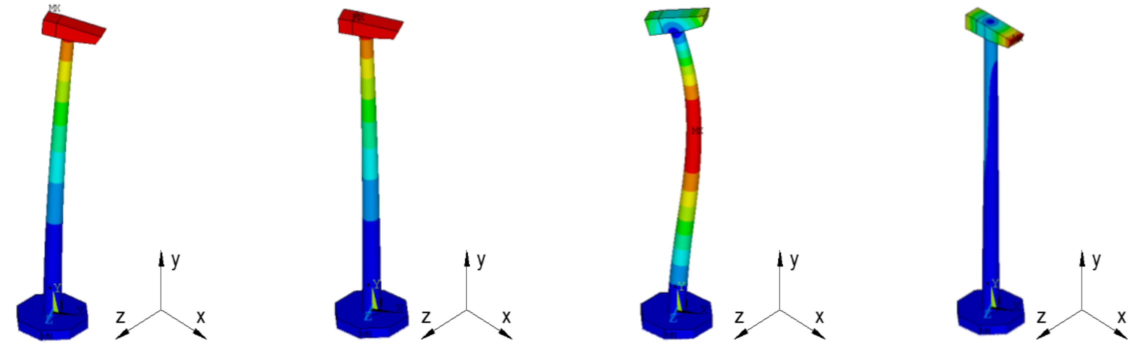
5 Natural frequencies and vibration modes

When the structure is excited by some external agent, it's possible that the excitation frequency coincides with one of the natural frequencies of the structural system, when that happens; the natural vibration mode is amplified, causing the system to resonate. To avoid this phenomenon, it is necessary that the frequencies of the dynamic loads not coincide with the natural frequencies of the system. Table 1 shows the first four experimental model frequency performed by Rebelo et al [5] and the natural frequencies of the numerical model.

Table 1. Numerical and experimental natural frequencies for the wind tower [1]

Natural Frequencies (Hz)	f_{01}	f_{02}	f_{03}	f_{04}
Numerical analysis	0.340	0.342	2.449	2.515
Experimental tests [5]	0.340	0.343	2.767	2.794

As can be seen from Table 1, that there is a good agreement between the experimental results and the structural model natural frequencies calculated using finite element simulations. That validates the developed numerical model, as well the results and conclusions obtained throughout this research work. Figure 5 presents that the bending vibration modes were predominant when the dynamic structural behavior of the wind tower was investigated.



1st Mode (f_{01}= 0.340Hz) 2nd Mode (f_{02}= 0.342Hz) 3rd Mode (f_{03}= 2.449Hz) 4th Mode (f_{04}= 2.515Hz)

Figure 5. Vibration modes of the wind turbine tower numerical model

6 Non-deterministic dynamic analysis

The wind turbine first vibration mode [f_{01} = 0.340 Hz: bending effects; see Fig. 5] represents the main peak of energy transfer of the dynamic response, is also noted that this energy transfer become larger as the wind velocity is increased. Initially, twenty series of non-deterministic wind load were generated, based on appropriate statistical treatment.

Loads were considered acting in the positive direction of the global X-axis, Fig. 2 presents this clearly. To perform the dynamic analyses on the investigated structural model, the software ANSYS finite element program [3] was used. Figure 6 shows the maximum displacements in the time and frequency domain for the velocity equal to 35 m/s [126 km/h].

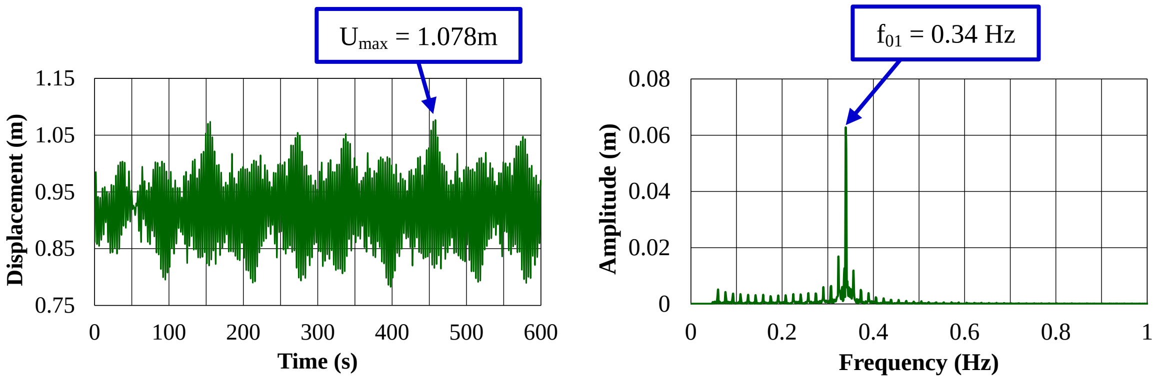


Figure 6. Maximum horizontal translational displacement [V = 35 m/s (126 km/h)]

The results of the dynamic analysis show that the maximum displacements were obtained at the top of the wind tower. The maximum von Mises stress values have occurred at the access opening of the wind turbine tower for all investigated velocities. It must be emphasized that there are connection flanges acting as stiffeners, aiming to stiffer this particular steel tower region. Figure 7 shows the maximum stress value for the velocity of 35 m/s [126 km/h].

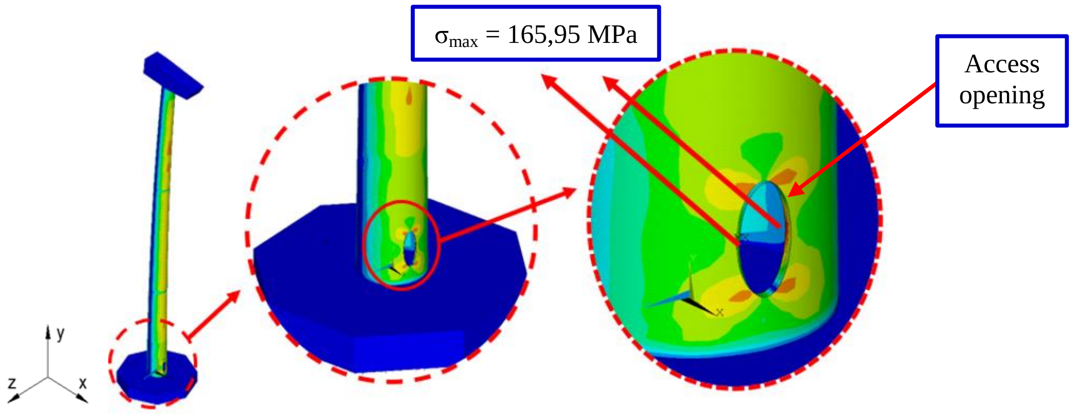


Figure 7. Non-deterministic dynamic forces in the time domain

Figure 8 presents the results for both the horizontal maximum displacements and the maximum von Mises stress for all investigated velocities. A point to be noted is the "jump" in the displacement and stress values between the velocities of 24 m/s [86 km/h] and 25 m/s [90 km/h], which also occurs in the static analysis. This "jump" is related to the modification in the applied loads generated by the rotor from the operational phase to the survival phase. The Eurocode 3 [6] establishes a maximum translational displacement value equal to 1.523 m for current metal towers and IEC 61400-2 [7] was used to calculate and verify the stress results, considering the recommended limit equal to 239.06 MPa.

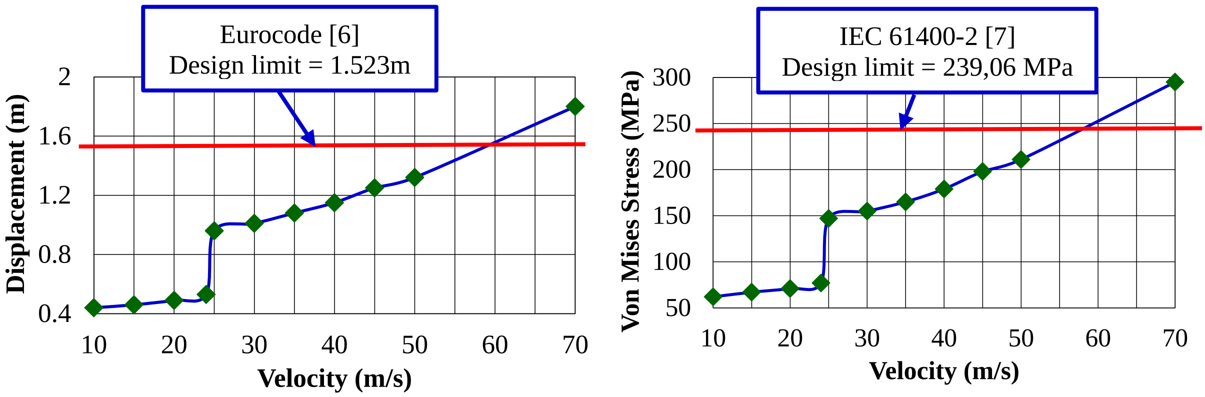


Figure 8. Dynamic analysis results for all velocities profile

It can be concluded that for the velocities of 10 m/s [36 km/h] to 35 m/s [126 km/h], usual velocities in Brazilian territory, the wind tower project attends the recommended limits for displacements. It must be emphasized that the maximum stress values calculated in this study do not induce plastic hinge formations in the tower structural sections. However, when the velocity of 70 m/s [252 km/h] was considered, such as hurricanes, the calculated maximum displacements exceeded the design limit value.

7 Fatigue analysis

Structures subjected to cyclic loads (stress or deformation cycles), can be susceptible to the phenomenon of fatigue. This way, having in mind that the non-deterministic wind loads induce the steel tower to stress cycles, through the loading and unloading of the structure, a fatigue analysis was performed in this investigation.

The fatigue analysis was developed following the classic methodology for fatigue damage assessment in structures due to effects caused by actions of varying amplitude. It is also based on the use of SN-type curves and Palmgren-Miner linear damage rule, based on the use of the Rainflow cycle counting algorithm [1].

In the fatigue analysis the Eurocode 3 [6] recommendations were used to calculate the accumulated damage and the service life of the structure in years. Figure 9 presents the service life of the investigated structural system, for each studied non-deterministic wind velocity profile. The DNV-GL [8] recommends a design lifetime of 20 years, which is generally assumed as a basis for dimensioning steel towers.

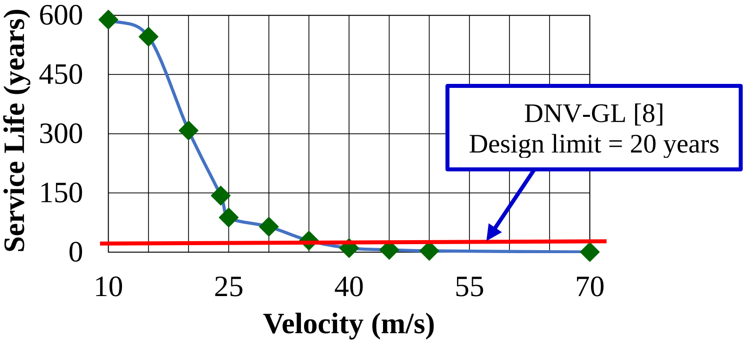


Figure 9. Tower service life for all velocity profiles

Based on the results presented in the Fig. 9, only velocities higher 40 m/s [144 km/h] don't attend the design limit. It is worth mentioning that the structure isn't subjected constantly to wind loads of this magnitude, and for the velocities 10 m/s [36 km/h] to 35 m/s [126 km/h], usual velocities in Brazilian territory, it was concluded that the wind tower project attends the recommended limits and it is viable to be used in Brazil.

8 Conclusions

This research work investigated the dynamic structural behavior of a steel tower to support a wind turbine with a height of 76.15 meters, when subjected non-deterministic wind loads. The tower presents low natural frequencies values, with fundamental frequency of 0.34 Hz. Thus, the main conclusions of this paper are:

1. Considering the wind velocities of 10 m/s [36 km/h] to 35 m/s [126 km/h], usual velocities in Brazilian territory, the wind tower project attends the recommended limits for displacements, and the maximum stress values do not induce plastic hinge formations in the tower structural sections.
2. The fatigue analysis shows that the service life of the structure decreases as the wind velocity increases. However, considering velocities in Brazilian territory (10 m/s [36 km/h] to 35 m/s [126 km/h]), it's concluded that the steel tower structural design attends the recommended design limit.

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