XLI
CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Optimized Structural Design of Lattice Towers for Wind Turbines

Tenorio C. Mayara[1], Cavalcante A. A. Marcio[2]

[1]*Campus of Engineering and Agricultural Sciences, Federal University of Alagoas*
BR-104, Rio Largo, 57100-000, Alagoas, Brazil.
mayara.tenorio@ceca.ufal.br
[2]*Campus of Engineering and Agricultural Sciences, Federal University of Alagoas*
BR-104, Rio Largo, 57100-000, Alagoas, Brazil.
marcio.cavalcante@ceca.ufal.br

Abstract. Wind energy is a valuable renewable energy resource, and it has been recently explored in Brazil, with a strong tendency to increase in the next decades, considering the Brazil's potential. The most common way to explore wind energy is through wind turbines, usually designed to have maximum efficiency. The tower is an essential part of the wind turbine design, once it defines the wind turbine efficiency and must be designed to resist to different loadings, responding for 30% of the wind turbine cost, approximately. This work presents a structural optimization study of steel lattice towers of wind turbines within a framework based on the strength of materials and the finite element method for the tower's structural analysis, besides optimization techniques, to minimize the tower's weight. Some comparisons are made with an optimized aluminum lattice tower. The minimization of the tower's weight through the employment of optimization techniques allows a reduction of the costs with inputs, transportation, assembling, and maintenance of the tower, especially those installed in remote areas with difficult access, besides contributing to the study of this technology.

Keywords: Renewable energy, wind turbine, lattice tower, structural optimization.

1 Introduction

In the mid-1980s, scientific evidence linking greenhouse gas emissions from human activities to global climate change began to raise public concern [1]. One of the ways found to mitigate this problem was the use of renewable sources for electricity production. Among these sources is wind energy produced from the transformation of the kinetic energy of wind into mechanical energy and finally into electrical energy. According to data from the International Renewable Energy Agency [2], the installed capacity of wind energy worldwide increased by 250% between 2010 and 2019.

Wind energy is obtained through the wind turbine, and one of its main components is the tower. It is responsible for adequately positioning the wind turbine for maximum energy extraction while also having to withstand different loads such as the weight of the turbine and the drag force caused by the wind. According to Feijó et al. [3], the tower presents a significant cost, estimated around 20% to 30% of the project's total value.

The material most used in the manufacture of wind turbine towers is steel, but it can also be employed reinforced concrete or even hybrid structures (concrete and steel). From the structural point of view, wind towers can be tubular, tripod, lattice, and gabled [4].

Given the importance of the tower and its cost in the final design of a wind turbine, this work aims to present a computational tool that was developed to provide lighter structural solutions for steel lattice towers, considering the principles of structural mechanics.

2 Methodology

The lattice tower studied in this work is ASTM A36 steel and has the following characteristics: (I) square base; (II) slender bar elements, with constant thickness, variable length, and which are in joints (knots); (III) constant cross-section area. The external forces considered in the tower were the weight of the nacelle-rotor combination of a small wind turbine, model Skystream 3.7™ [5], and the drag force caused by sweeping the blades of the wind turbine. Fig. 1 shows a representation of the lattice tower and the assessed forces. The structural analysis was performed for towers of 2 to 7 sections with a height (H) of 12 meters.

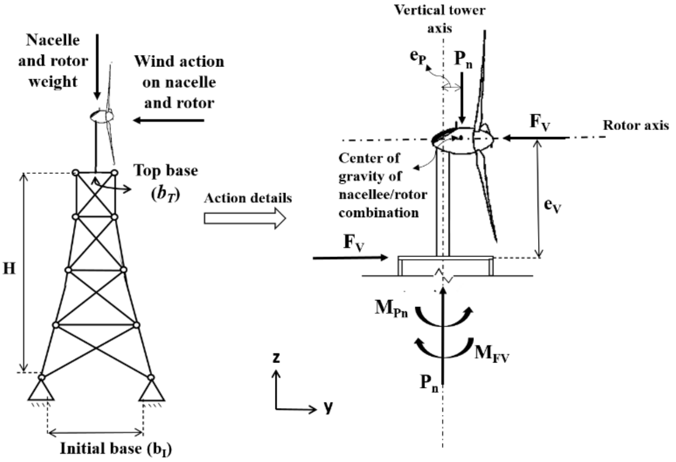

Figure 1: Illustrative representation of the tower and lattice model calculation.

The drag force (N) acting on the top of the tower can be calculated by eq. (1) [6].

$$F_V = \frac{1}{2} \rho \, V_k^2 A_r n_p. \tag{1}$$

With ρ being the air density (kg/m³), A_r the rotor sweep area (m²), V_k the characteristic wind speed (m/s) and n_p the number of rotor blades. The characteristics wind speed is calculated according to eq. (2), where V_0 is the basic wind velocity and S_1, S_2 and S_3 are correction factor detailed by NBR 6128 [7] standards, which considers the topographical characteristics of the tower's location, roughness factor and the safety factor applied on the structure, based on statistics conception, respectively

$$V_k = V_0 S_1 S_2 S_3. \tag{2}$$

The basic wind speed varies according with the analysis criteria. For the resistance criteria, the calculation is made by the ultimate limit state method, according with NBR 6128 [7]. It is followed using Brazil's isopleths map. For the calculation of the maximum displacement at the top of the tower, the method used is the service limit state, used following NBR 8800 [9], in which the basic wind speed is the nominal wind speed of the turbine. It was considered that the tower's actions are equally distributed among the four knots at the top of the tower. The resulting forces acting on each of the four knots are obtained from eq. (3), (4) and (5).

$$F_{RX} = 0. \tag{3}$$

$$F_{RY} = \frac{-Fv}{4}. \tag{4}$$

$$F_{RZ} = \frac{P_n}{4} + \left(\frac{M_P - M_V}{2b_T}\right). \tag{5}$$

P_n is the force weight (N) of the rotor nacelle, M_P is the moment generated by the weight force (N.m), M_V is the moment generated by the drag force (N.m), and b_T is the top base of the tower (m).

Starting from the calculation of the external forces acting on the tower, it is possible to apply the finite element method to find the global displacement vector, as shown in eq. (6) [8].

$$\{ u_n \} = [K]^{-1} \{F\}. \tag{6}$$

Where {F} is the vector with the global force components in the x, y and z directions; [K] is the global stiffness matrix; {u} is the vector with the global displacement components in the x, y and z directions. Using the solution of the global system of equations, it is possible to evaluate the axial displacements, as shown in eq. (7) [8]. Later, it is possible to obtain the axial forces acting on the bar elements, demonstrating by eq. (8) [8].

$$\{u_n\}=\begin{Bmatrix} u_1^e \\ u_2^e \end{Bmatrix}=\begin{bmatrix} cos\theta_{1x} & cos\theta_{1y} & cos\theta_{1z} & 0 & 0 & 0 \\ 0 & 0 & 0 & cos\theta_{2x} & cos\theta_{2y} & cos\theta_{2z} \end{bmatrix}\begin{Bmatrix} u_{1x} \\ u_{1y} \\ u_{1z} \\ u_{2x} \\ u_{2y} \\ u_{2z} \end{Bmatrix}. \tag{7}$$

$$\begin{Bmatrix} f_1^e \\ f_2^e \end{Bmatrix}=[k^e]\begin{Bmatrix} u_1^e \\ u_2^e \end{Bmatrix}. \tag{8}$$

As each bar element contains 2 nodes, u_1^e and u_2^e represent the nodal axial displacements of the element; θ_{1x}, θ_{1y} , θ_{1z}, θ_{2x}, θ_{2y} and θ_{2z} represent the inclination of the element relative to the global axes x, y and z; $[k^e]$ represents the local stiffness matrix of the bar element; u_{1x}, u_{1y},u_{1z},u_{2x}, u_{2y} and u_{2z} represent the local displacements in direction x, y and z.

After obtaining the internal forces, the criteria of traction, compression, buckling [9], and maximum displacement at the top of the tower [10] are used to find the characteristic dimension of the cross-section of the bar element. The criteria are based on NBR 8800 [10] that gives the safety factors to the calculations. The eq. (9) is used to select the final characteristic dimension that satisfies all the analysis criteria.

$$d_k = MAX(d_{kT}, d_{kC}, d_{kF}, d_{kD}). \tag{9}$$

Where $d_{kT}, d_{kC}, d_{kF}, d_{kD}$ are the characteristic dimensions found based on traction, compression, bucking and maximum displacement at the top of the tower, respectively.

Finally, d_k is used for the calculation of the volume of the bar elements of the structure.

2.1 Structural Optimization

Structural optimization consists in a tool capable of finding the best solution for the structure from a numerical/mathematical process, which follows constraints associated with the project. In engineering, optimization aims at reducing project costs by meeting the safety criteria of the structure. The search for the optimal structure was carried out using the MATLAB® optimization toolbox.

The function used was the *PSO*, and from it, the optimal volume for the structure was found. The restrictions associated with the ultimate and service limit states have been incorporated into the objective function. Figure 2 shows the elements that were considered to the lattice tower problem.

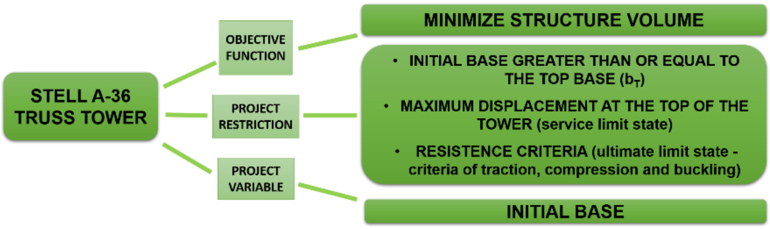

Figure 2: Elements of optimization applied to the *PSO* function.

The comparative study was carried out among bar elements with a solid square cross-section, leaked square, solid circular, and leaked circular, with the tower ranging from 2 to 7 sections.

3 Results

The results of the analysis, found with the *PSO* function, show that as the number of sections increases, the tendency is that the structure's volume decreases due to the reduction in the sizes of the elements. Figure 3 shows the graphical analysis of the optimum volumes as a function of the number of sections. For leaked sections, the thickness used was 3 millimeters.

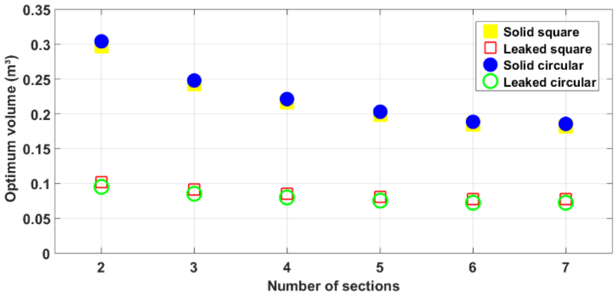

Figure 3: Optimum volumes as a function of the number of sections.

The leaked circular section presents the best result amid all the tower configurations studied because it shows the highest moment of inertia for the same amount of material. The optimal volume found, among all the analyzed cross-sections, was for the 7 sections trussed tower. The resulting ordered pair was optimum volume = 0.072725 m³, for initial base = 1.0359 m. From the results in Fig. 3, it was possible to obtain a graphical analysis of internal stresses acting on the bar elements for the 2,3, 4, 5, 6 and 7 lattice sections with leaked circular section, as shown in Fig. 4. The color scale used is darker the blue color for higher the compression, and darker the red color for higher the traction.

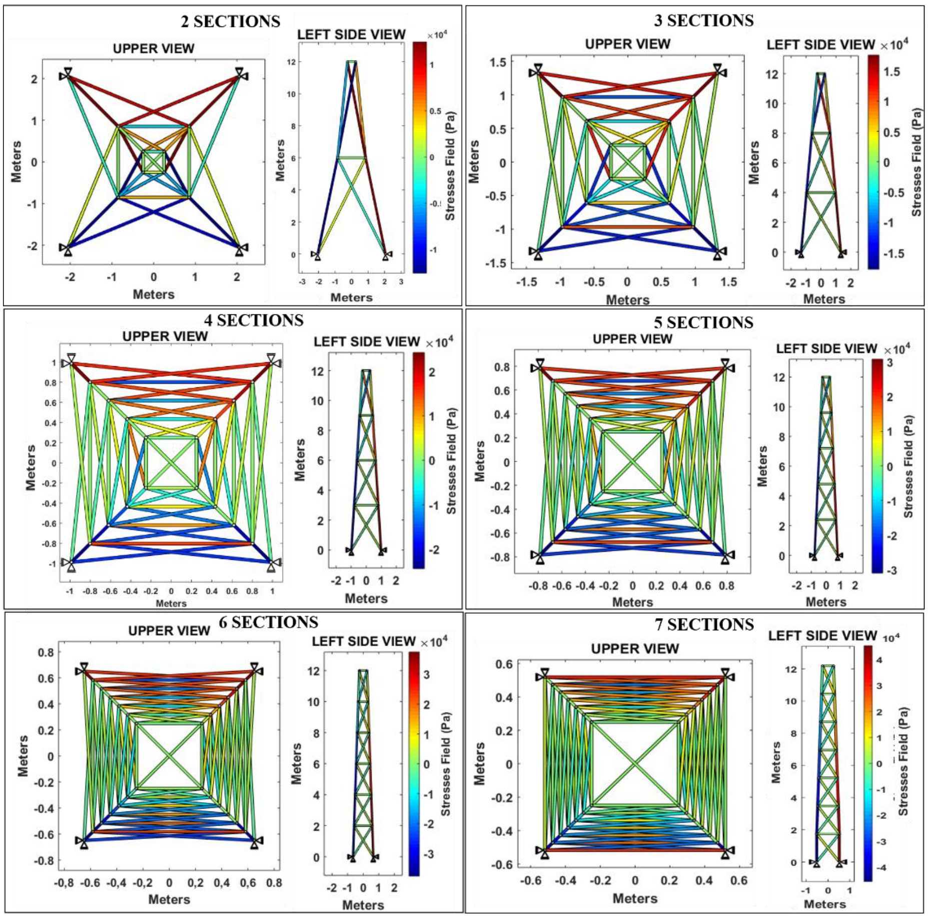

Figure 4: Graphic analyses optimum volume. Left side and upper side views of the internal stresses for lattice towers with 2, 3, 4, 5, 6 and 7 sections.

Figure 4 shows that, regardless the number of sections, the most solicited elements in the structure are those in the base. It can also be observed that with each section added, the stress applied on each element increases, this occurs because by reducing the length of the element the force will be distributed over smaller areas.

Figure 5 shows the optimal characteristic dimensions per section of the bar element cross-sections. This shows that the cross-section of the bar element tends to decrease significantly as the first sections are added. After that the reduction continues but becomes less significant.

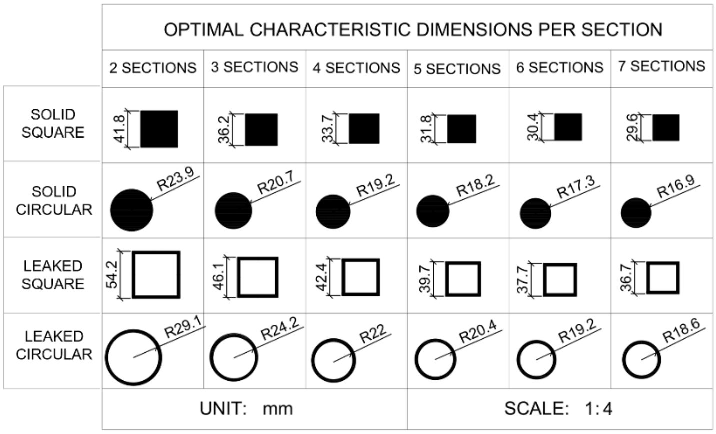

Figure 5: Optimal characteristic dimensions per number of sections.

4. Conclusion

According to the tool developed and applied to structural optimization, the reduction in volume with the number of sections occurs because as the number of sections increases, the size of the elements decreases. The reduction in the element length will cause a decrease in the volume calculation because there is a relationship between length and volume, affecting the characteristic cross-size dimension. The tool provides optimal values for the volume of the structure and presents graphical outputs that allow visual analysis of the data.

From the graphic analysis of the volumes, it is possible to conclude that volumes resemble for the leaked and solid configurations. This phenomenon occurs because of the moment of inertia employed in the buckling criteria. This graphical analysis also allows to conclude that the cross-section, at all the analyzed lattice tower configurations, that offer the best performance is the leaked circular. This is due to the section, among the analyzed ones, shows the highest moment of inertia.

In the graphical analyses of the internal stresses acting on the bar elements, it is possible to point out that, at all configurations, most solicited elements are those closest to the base. It is also possible to see that there is a reduction in the length of the initial base of the tower according to the increase in the number of sections.

The addition of sections leads us to an asymptotic behavior; that is, from a certain number of sections, the addition of sections does not lead to a considerable decrease in the structure's optimal volume.

References

[1] Brazil, Ministry of Science and Technology and Ministry of Foreign Affairs of the Federative Republic of Brazil. Convenção sobre Mudança do Clima.

[2] International Renewable Energy Agency. Statistics Time Series.

[3] B. P. Feijó, J. B. C. A. Lima, A. M. C. Melo and E. JR. Parente. Otimização estrutural de torres de aço tubulares para geradores eólicos. Argentine Association of Computational Mechanics, v. 29, p. 781-792, 2010.

[4] D. A. C. Pestana. Sistemas estruturais para torres eólicas. Dissertation (Master's in civil engineering) – University of Madeira. Funchal, 2016.

[5] Xzeres Wind. SKYSTREAM 3.7 Owner's Manual, North America and Europe Edition. United States of America, 2013.

[6] J. Song. The Comparison and Study of Cone-Shaped Tower and Truss-Type Tower of 1.5 MW Wind Turbine Generator (in Chinese). PhD Thesis. Baotou: Inner Mongolia University of Science and Technology, 2012.

[7] Brazilian Association of Technical Standards. NBR 6123:1988. Forças devidas ao vento em edificações. ABNT. Rio de Janeiro, 1988.

[8] Fish, J., Belytschko, T. Um Primeiro Curso em Elementos Finitos. 1 ed. LTC. Rio de Janeiro, 2009.

[9] Hibbler, R. C. Resistência dos Materiais. 7 ed. Pearson Prentice Hall. São Paulo, 2010.

[10] Brazilian Association of Technical Standards. NBR 8800:2008. Projeto de Estruturas de Aço e de Estruturas Mistas de Aço. ABNT. Rio de Janeiro, 1980.