Zhongguo Kuangye Daxue Xuebao
Journal of China University of Mining and Technology

2024 | Vol 29 | Issue 2 | Page 139-151
Journal Homepage: https://zkdx.ch/
DOI: 10.1654/zkdx.2024.29.2-14

Structural Analysis of New Octagonal Pre-Stressed Concrete for On Shore Wind Turbine Tower Using Computational Fluid Dynamics (CFD)

Abdelrahman Eissa*
Civil Engineering Department, Sphinx University in Assiut, Regional Service Road New Assiut City New, Assiut Governorate 71515, Egypt
*Corresponding author

Arafa El-Helloty
Department of Civil Engineering, Faculty of Engineering, Al-Azhar University, Cairo, Egypt

A. Ehab
Civil Engineering Department, Badr University in Cairo (BUC), Badr City 11829, Egypt

Abstract

To produce electricity, the wind turbine's tower needs to be sturdy enough to withstand the forces generated by the generator located at the tower tip. The tower height must be sufficiently elevated to capture more robust winds at more intense velocities. In addition to its ability to withstand wind and challenging weather conditions, it must also be cost-effective. Consequently, these results mention the cost overrun of the turbine. Therefore, this article presents the new version of the octagonal cross-section wind turbine tower, which effectively tackles weaknesses of previous studies in concrete wind turbine tower design and tackles obstacles concerning construction intricacy, transportation and installation, fluctuating wind loading, stress concentration, and material usage. In this study, dead, wind, fatigue, buckling, and seismic loads are considered for a tower with a 100-meter height and a 3.6 MW generator. The wind tower's stress, deformation, buckling, and fatigue limits will be analyzed to verify compliance with design codes. Finally, the result mentioned that the newly proposed across-section was very effective. The ratio of about 50% and 30% decreasing ratio in the deformation and stress respectively smaller than the allowable stress.

Keywords: Concrete Structures, Horizontal Axis Wind Generators, Ansys, Finite Element Analysis

1. Introduction

Wind energy is a highly sustainable and environmentally friendly way to generate electricity. It stands out from other energy sources due to its affordability, low environmental impact, and ease of use. Not only does it not produce harmful pollutants or contribute to global warming, but it also provides a cost-effective and efficient ` for clean energy production. Related to the many changes happening in the world in recent years, like climate change, global warming, and different emissions, the development of sustainability and environmental impacts are under focus. Renewable energy sources (geothermal, wind, and solar) and decreasing the environmental impacts, are attractive items for increasing the efficiency of energy. The design of a wind turbine tower can significantly impact the installation costs of wind turbines. It is important to carefully evaluate design choices, including tower height, materials, type, foundation, transportation, structural requirements, maintenance considerations, regulatory compliance, and scalability, to ensure that project goals and budgets are met while optimizing performance and cost-effectiveness [1].

Finite Element Analysis has been done to study the behavior of an octagon cross-section by [1]. The study proposed an octagon cross–section with an internal ribs turbine tower and compared it to a traditional circular reinforced concrete cross-section model of concrete towers for a 100 m height and 3.6 MW power output. Concrete towers are easier to construct and analyze, exhibit excellent dynamic behavior, and are the preferred choice to solve transportation issues [2].

Also, it has been demonstrated that close changes in sections of a loaded structural member occurred, with different distributed stresses from the peak to downs and within average in-between. Usually, the peak stress or stress concentrations occur at the sharp corners, regions of cracks, holes, and notches. Stress concentration is one of the big problems facing designers to make it safe and the main cause of damage to the structure. Many previous researches dealt with this problem in different effective and ineffective ways. So, the main concept of this study is a modification of the traditional octagonal cross section by adding internal ribs at the corners.

The dimensions of these ribs are calculated related to the analysis of the subjected stress at the corners of the octagonal by the first analysis method and previous studies. Therefore, the internal rips at corners increase cross-section rigidity and reinforce against lateral loads, thereby reducing stress concentration in the corners. These features also help to reduce the weight of the structure while maintaining its strength and stiffness. It also contributes to the overall uniformity of the structure, making it more resistant to external forces.

In another way, previous studies show that pre-stressed concrete towers are a better choice than steel for wind turbines above 80 meters in height [2]. A suitable tower related to economical, durable options, with 1oo m height is a concrete tower. The concrete tower is a more cost-effective and long-lasting alternative, especially when the hub’s height reaches 100 meters. Despite these findings, but still, there are some concerns about the call still engines of implemented concrete towers [1], [3] and [5].

In construction, the improvement of shear strength, controlling of deformation, enhancement flexure ductility, and crack closure upon unloading are the main items that are covered by using pre-stressed concrete to achieve the required structural properties. These properties are crucial for ensuring that structures can withstand natural disasters such as earthquakes, windstorms, and overflows and provide a longer life span for structures that experience fatigue and dynamic loads. Ensuring the safety and reliability of these structures should be an utmost priority [6] and [7].

2. Literature Review

A tower is one of the key components of a wind turbine, with more than a percent of the turbine's total cost [8]. It is a vital component of safety for the turbine that is subjected to aerodynamic loadings. This makes the tower's design (structural behavior) a major factor in determining the final cost of energy. A survey of technical literature reveals that significant studies on wind turbine technology, whether it is any direction horizontal or vertical axis, focused on the performance of these turbines subjected to aerodynamic loading. Researchers use experimental testing and Computational Fluid Dynamics (CFD) numerical simulation to investigate these aspects [3], [9] and [10].

In recent years, the scientific community has shown a growing interest in examining the structural design and behavior of wind turbines, which reflect on the cost of it. Many of these research endeavors have concentrated on assessing the structural design behavior, both in static and dynamic conditions, of either the rotor blades or individual blades, treating them as standalone components. Conversely, numerous wind energy researchers have directed their focus toward understanding how the tower structure responds to various dynamic loads [9], [10]. The main objective of this research is to propose a pre-stressed concrete wind turbine tower in an octagon cross-section with internal ribs at corners, that is a good alternative for steel and concrete tubular wind turbine towers exceeding 100 m height, with an investigation of the dynamic behavior of the proposed section with a 100-m-high pre-stressed concrete tower of 3.6 MW wind turbine when subjected to wind excitation which no previous studies had been dealt with this idea. A numerical modal analysis using a three-dimensional (3D) Finite Element (FE) method has been used in this study.

In the field, wind turbine towers are typically constructed using tubes that are made from steel for their quick assembly. Then, the tube segments are transported to the construction site and erected with the assistance of cranes. Nevertheless, the rising production of energy needs has necessitated the construction of larger and taller towers. This, in turn, has led to an increase in the cross-sectional diameter of these towers to ensure they can safely withstand the dynamic loads and stresses imposed on them [1] and [3].

Another design proposal for wind turbine towers is a triangular cross-section system, consisting of columns at all corners, as proposed by [4]. The philosophy adopted in this study used an aerodynamic transverse section to reduce the wind force on a high-rise building, thereby decreasing its weight and stress. The study examined the different heights of the tower for 3.6 megawatts, comparing their performance with that of a traditional conical metallic tower with the same height. In another study [2] a new support structure system for wind turbines has been proposed [3]. This system was made of pre-stressed concrete and featured octagonal tower sections. The design included internal side stiffeners which resulted in a 30% reduction in the cost for an optimized tower. The research also optimized the pre-stressed force in the tower and the design of the pre-stressed concrete tower. However, the study did not address the stress concentration problem.

3. Description of the System

The proposed system in this manuscript is an octagon cross-section of a pre-stressed concrete support structure system with ribs at the corners that increase all beneficial concrete qualities from prior research investigations, now with added cross-section and dimensions. The main criteria, primary dimensions estimation, and geometry of the proposed section in this research are investigated according to, firstly, the previous work [1] and [3]. Secondly, due to the principle analysis of the external stresses on the cross-section. So, when a structural member is subjected to load, stress concentration arises in the vicinity of variations in its cross-section, such as holes, notches, sharp corners, cracks, and other irregularities. This stress concentration results in peak stresses that surpass the average stress across the section by a significant margin [1]. Also, to address the challenges of integrated stiffness and self-weight of pre-stressed concrete towers, it is suggested to attach several pairs of ribs symmetrically inside the tower, which helps to reduce deflection at the top of the tower [3]. To satisfy these previous studies, the authors suggested that the ribs will be at the corners of the octagon cross-section. Then, the first principles guided the authors to determine and estimate the dimensions of each rib at different heights of the turbine tower due to the below equations and stress calculations at various cross sections, and the second-order of moments also considered in these estimations, which is a result from deflections, are determined using an iterative procedure and equation. The next equations (as a function of height z) are the internal forces [11], used for the estimation of the ribs' dimensions:

$$P(z) = F_v + \int_0^{H-Z} w_v dy \tag{1}$$

$$V(z) = F_h + \int_0^{H-Z} w_h dy \tag{2}$$

$$T(z) = T \tag{3}$$

$$M(z) = M_T + F_T(H-Z) + \int_0^{H-Z} w_h (H-Z-y) dy + M(z)_{2nd\ Order} \tag{4}$$

$$M(z)_{2nd\ Order} = P(z) \times 0.75 \times (v_{top} - v_i) \tag{5}$$

Where,

v_i is the deflection of the ith section and top is the deflection of the tower top,
Fh: horizontal force at the tip of the tower,
Mt: the torsional moment at the tip of the tower, the volume of the Tower,
Z: tower height above the ground,
Mz: second-order moment.

The proposed system is designed to reduce the risks of the local buckling, due to deformation and reduce the seismic response of the system.

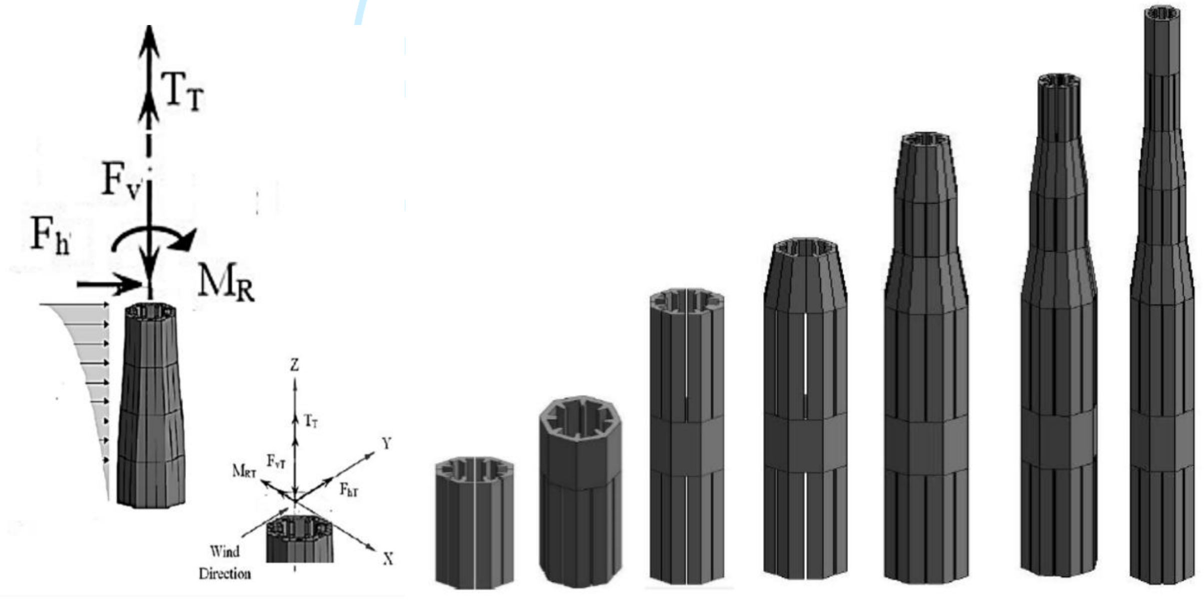

Fig. 1 (a) Proposed System, (b) Cross Section Analysis

Additionally, the system is designed to be cost-effective and environmentally friendly. The section of the tower has been suggested in such a way that it can be disassembled into eight identical parts with larger dimensions at the base, and four identical parts with the inverse relationship as the height increases the dimensions of the cross-section decrease. Parts can be transported to any location for reassembly purposes.

Additionally, the internal ribs at the corner enhance and reduce stress concentration issues as shown in Fig. 1, and Fig. 2, as we build structures with concrete, creating a conical shape by continuously changing the dimension of the cross-section and the tower can be challenging to fabricate and erect. To address the issue, cross-selection variation at heights 50-60m and 70-80m is only reasonable along the tower height, which makes the tower easier to erect, fabricate, and transport cross-section thickness of the structure varies between 50 cm at the base and 25 cm at the top for the web zone and 27 cm to 15 cm for the ribs all of these dimensions are related to the first principles calculations as described at the previous paragraph.

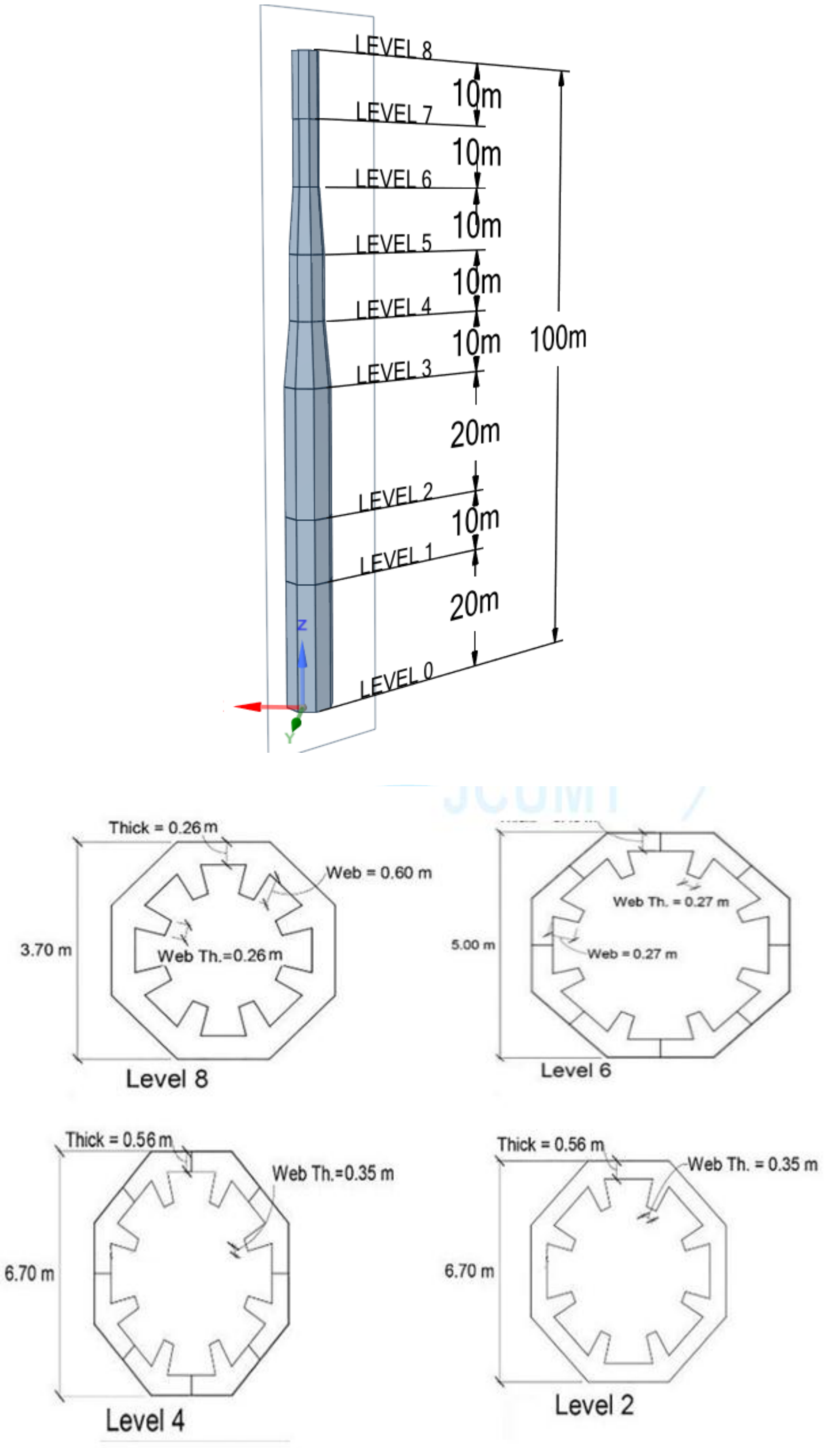

Fig. 2 Cross Section Dimensions

4. Methodology and Limitations

A new structural philosophy and methodology are changed for the design and analysis of an octagon with ribs in each corner compared to the circular cross-section of pre-stressed concrete wind turbine towers.

The design procedures are specifically presented to fit the new cross-section to ensure compatibility, transportation issues are meticulously accounted for, and fast erection time is guaranteed. The design methodology of a pre-stressed concrete tower follows the standards and limits given in codes such as IEC61400- ASCE 7-10, the ACI 318, and the IEC (2005), (NREL), the design parameters also have been determined and linked with these specifications and codes. The height of a tower is determined by several primary factors, these factors can vary depending on the tower's location, wind speed, and humidity. Therefore, it is essential to consider the wind profile and turbulence when determining the tower's height. Moreover, it is necessary to meet the classes of IEC 1, 2, and 3 conditions to ensure adequate insulation and protection from the elements.

The Finite Element Method enables the computation of strains, stresses, and potential failure modes under various stress levels and operational conditions. Ansys Workbench R2023® software was used for this study as it provides accurate and efficient results through its advanced capabilities and user-friendly interface, making it an ideal choice for complex research.

To achieve the aims of this research, various stages are taken, as illustrated in Fig. 4. The analysis is divided into four phases, which are: The first phase is a geometric phase this phase is interested in determining the parameters and material characteristics, and the output of this phase is the tower geometry and cross-section. Secondly, the determination of the external forces (force and moment) must be considered in the next phase. The third one is the neutral frequency of the tested tower. Then, check the stiffness of the tower's natural frequency and the pre-stress forces must be added with an estimated safety load factors related to ACI 318. Finally, the model will be created and ready to give its results.

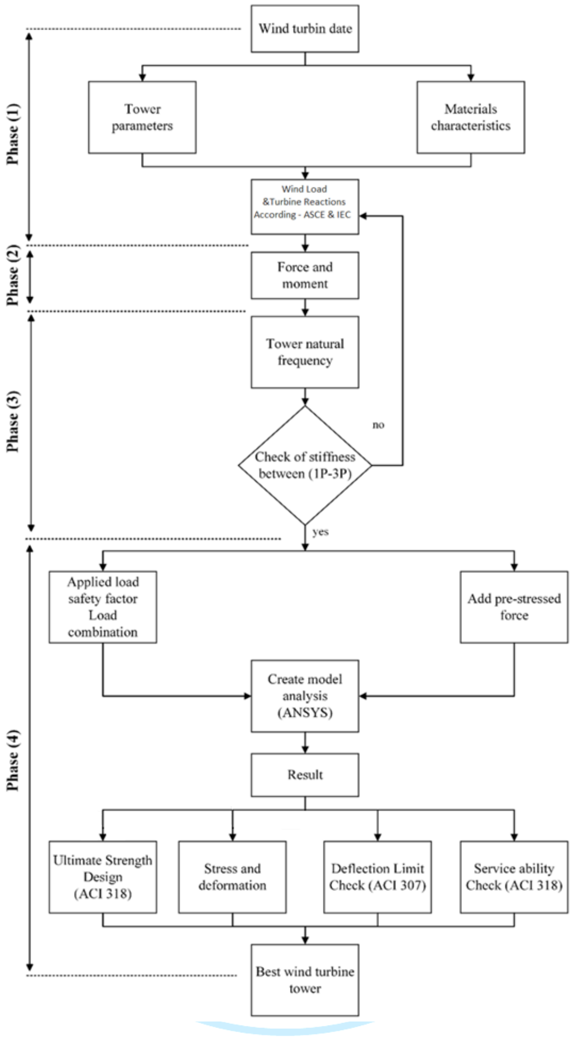

Fig. 3 Flow Chart and Methodology of study

5. Case Study

The wind turbine manufacturers typically provide comprehensive documents and information for a 3.6 MW wind turbine project, including product specifications, installation and maintenance manuals, safety documentation, performance data, electrical drawings, and environmental impact assessments. IEC 61400-1 and IEC6140 require consideration of multiple wind models in turbine design. This study focused on the two models of significant tower models, called extreme operating gust, and wind speed, shown and highlighted in Table 1. For this work, a load factor of 1.35 was used for wind turbine loads as IEC 61400-1 specified. The analysis included extreme wind speeds for operational and non-operational conditions for ultimate and service load combinations.

Table 1 Technical specifications of the wind turbine

Rated power	3.6 MW
Rotor Diameter	115 m
Cut in wind speed	2.5 m/s
Cut out wind speed	25.0 m/s
Rotor speed	13.2 rpm
Upper component	315113 kg
The height of tower	100 m
IEC Wind classes	I
Normal wind speed.	10 m/s
The extreme wind speeds (EWM)	59.5 m/s
The gust speed of the wind (EOG).	35.1 m/s

5.1 Material Properties

The concrete used in this study has specialized properties, including a minimum compression strength of 60 MPa (FC), a maximum water-cement ratio of 0.50, a minimum cover of 30 mm for reinforcement steel, and a minimum sheathing cover of 40 mm for pre-stressed concrete. The permitted maximum concrete stresses are 0.45 fc and 0.60 fc for quasi-permanent loads and regular loads, respectively. The yield stress for steel reinforcement is fy = 500 MPa, and fps = 1860 MPa for pre-stressing strands and tendons. It should be noted that the initial wind turbine specifications provided by IEC are not intended to be used as a full design, and these properties are given as input to ANSYS.

6. FEM Modeling

6.1 Tower Modeling

The revolution of computer technologies is the main core of the growth of numerical modeling and simulation for engineering systems. This technology simplifies many problems as wind turbines express complex structures related to their design and dynamic behavior and demand detailed FE modeling. Therefore, this study is modeled by using Ansys Workbench. The boundary conditions of the tower is modeled by fixed at the bottom of it to ensure safety, stability, controlled movement, and load distribution while also complying with industry standards.

6.2 Tower Meshing

The objective of utilizing CFX mesh is to generate meshes of superior quality that can precisely resolve boundary layer phenomena and conform to stringent quality standards [1]. CFX-Mesh can create meshes that consist of tetrahedra, prisms in the standard 3D meshing model, as well as hexahedra in the 2D meshing mode. For this investigation, an ANSYS advanced size function was employed to generate a tetrahedral mesh, given the intricacy of the model. This size function has demonstrated exceptional effectiveness in creating high-quality meshes around solid tower sections. Additionally, mapped face meshing was utilized for the tower faces to ensure a more uniform mesh, as recommended by ANSYS support. as shown in Figure 4. It's important to note that the results obtained from the finite element analysis depend on the selected discretization solution.

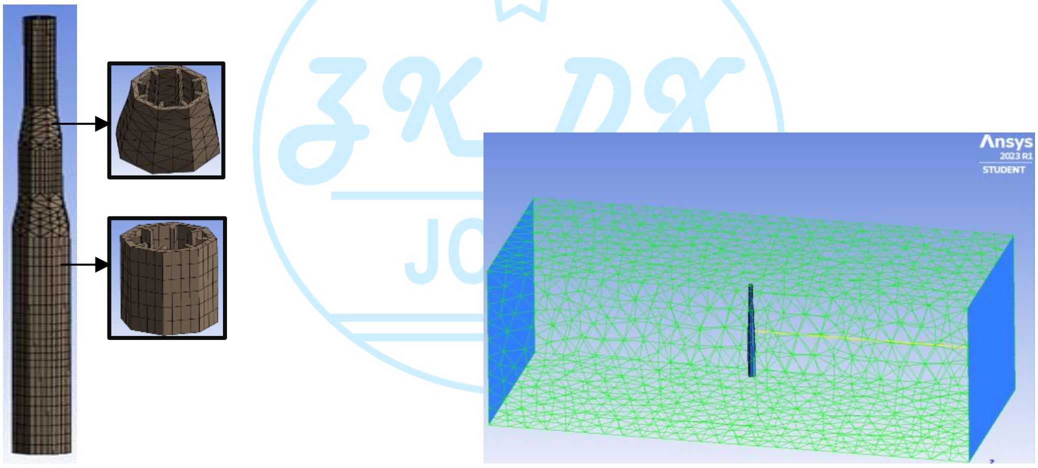

Fig. 4 Meshing of Tower

6.3 Turbine Loads

To assess the tower, it is necessary first to determine the reactions of the wind tower's turbine; these reactions can then be applied to the tower as shown in Figures 5 and 6. The generator utilized in this study has 3.6 M.W rate power. Reaction forces for the turbine have been obtained from technical studies published by the National Renewable Energy Laboratory (NREL), authored by Malcolm and Hansen in 2006, as well as by Lanier in 2005, as shown in Table 2.

Table 2 Turbine Reactions

Forces	E W M	E O M
The Horizontal Force of Tower (kN)	1088	1198
The Overturn Moment (KN/m)	16767	9913
The Twisting (KN/m)	5961	1597
The Axial Force of Tower (KN)	3155	3129

The gravitational loads and the aerodynamic loads (that appeared as the action of the wind dragged) can drag and lift forces are the main loads acting on the tower. Also, the aerodynamic loads are divided into a pair of main categories, the first one includes the loads acting directly on the tower and the second one is the rotor loads with further transferred that acting at the upper part of the tower. All of these forces and moments acting on the turbine are illustrated in Fig. 5 and Fig. 6.

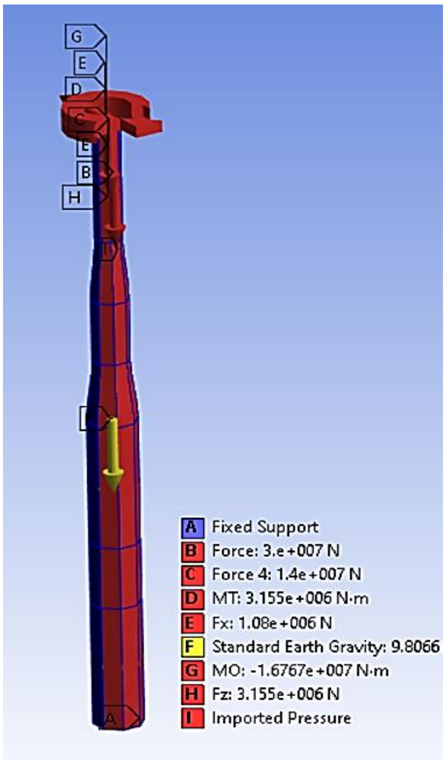

Fig. 5 Loads Action on Tower

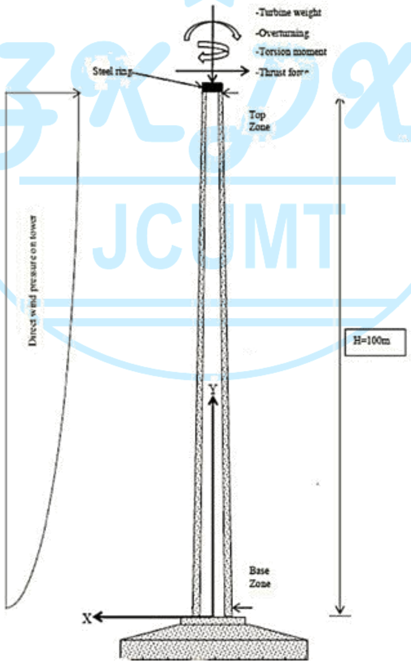

Fig. 6 Tower Loads Model

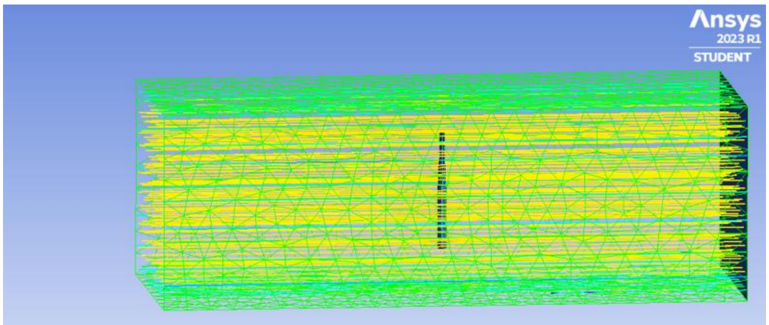

Fig. 7 FEM Model

The wind pressure exerted on the turbine tower was simulated using the Computational Fluid Dynamics (CFD) technique through ANSYS Fluent software as Shown in Figure 7. The tower was represented as a fluid domain to analyze the wind flow patterns, pressures, and velocities surrounding the structure. The analysis also included static forces that considered the tower's gravitational load and any external loads acting upon it to capture the tower's structural response to wind pressure. By combining the CFD simulation with the consideration of static forces, a comprehensive assessment of the turbine tower's overall structural behavior under the combined influence of wind pressure and static loads was obtained.

7. Result and Discussion

According to ASCE, the load factor is equal to 1.6 at the ultimate limit state (ULS) method at analyzing pre-stressed concrete towers using the finite element analysis. This will help calibrate the model to accurately predict and anticipate the deformation and stress at different points along the tower's height, as well as the initial pre-stressed force and reactions in various directions. Also, an operation condition under normal wind conditions must be simulated under the serviceability limit state (SLS) with safety factors modified to completely with IEC conditions.

The Ultimate load: $0.9D + 1.6W + 1.35TWL$……………………….….. (1)

The Working load: $0.6(1.0D + 1.0W + 1.0TWL)$ …………………… (2)

Where, TWL= wind-induced generator loads, According to ASCE specifications.

7.1 Natural Frequency of tower and Mode Shape

Natural frequencies are significant outcomes and are consistently a point of interest when designing tall structures, including tower structures and other high-rise constructions. To avoid resonance induced by vibrations, it is critical to ensure that the tower's natural frequency is distinct from the harmonic vibrations linked to the rotor. The stiffness of a wind turbine tower is influenced by the rotation frequency of the rotor (1P) as a lower limit and the frequency associated with the blade movement (3P) as an upper limit with a safety distance of –15% and %. The study uses a 3.6MW turbine with a feasible acceptable natural frequency zone tower. The working frequency is soft-stiff and ranges from 0.22 Hz to 0.66 Hz.

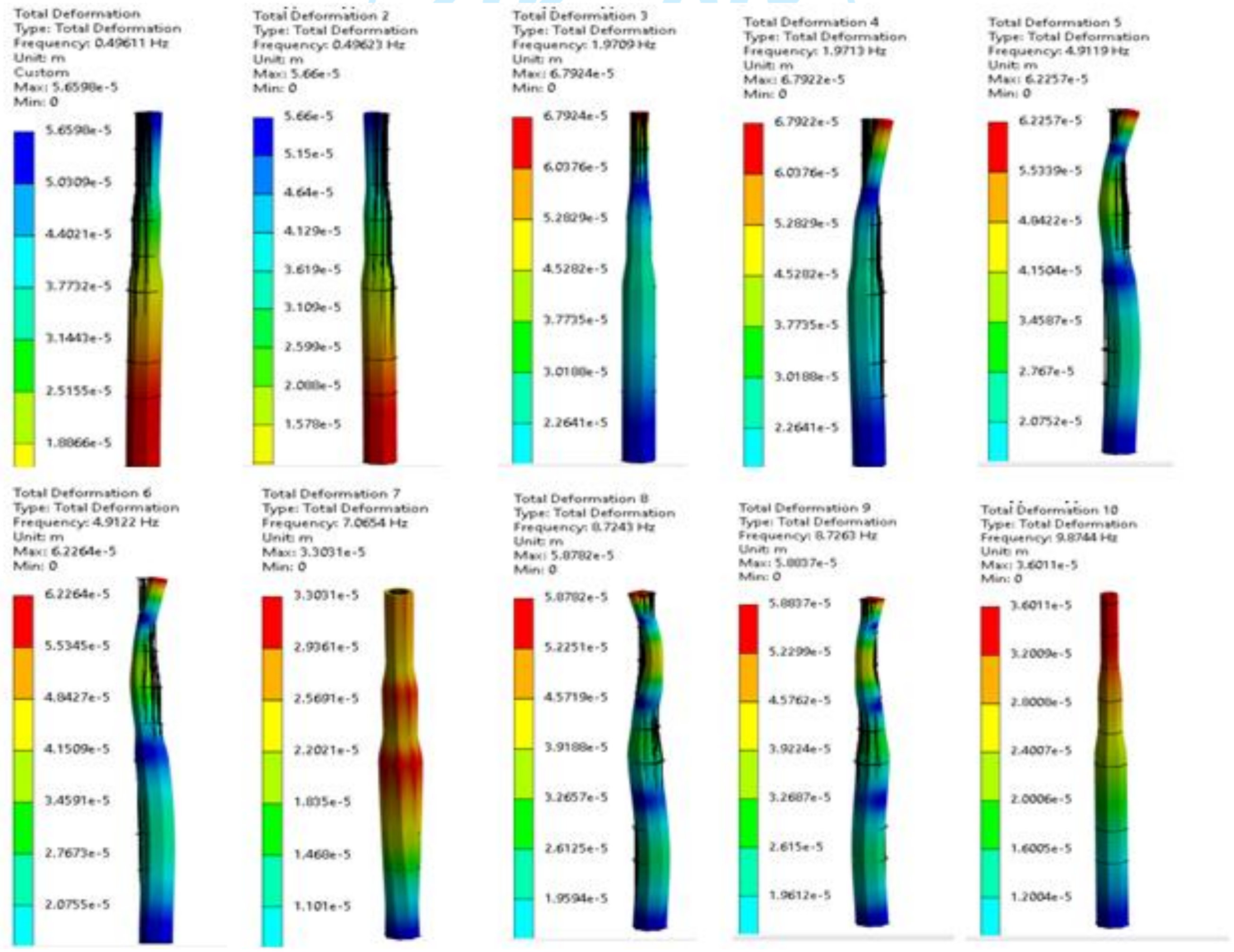

Fig. 7 Tower’s mode shapes

Table 3 Mode Shape Description

Mode	**Frequency (HZ)**	**Type of mode shapes**
1	0.4	Lateral
2	0.4	Lateral
3	1.9	Lateral
4	1.9	Coupled (lateral - vertical)
5	4.9	(Lateral with vertical)
6	4.9	(Vertical with Torsion)
7	7.0	Torsion
8	8.7	(torsion with lateral)
9	8.7	Lateral
10	9.8	Vertical

Table 3 presents the first ten-mode shapes and their corresponding frequencies in ascending order for the tower structure. The tower's lowest natural frequencies are evenly distributed across each order, ranging from 0.49 to 9.8 Hz. Notably dramatic, there is a close relationship between the natural frequency of 1st and 2nd, 3rd and 4th, 5th and 6th, 8th and 9th in the mode shape motion, respectively... This is due to the tower's axial-symmetrical structure, which produces vibration mode shapes that are symmetrical and in line with the mechanical structure, These values, ranging from 1P to 3P (0.220-0.660), satisfy all the criteria and requirements of the wind turbine industry. The values of frequencies of this work were compared to towers with circular cross-sections [6], it has been noticed that wind turbine towers with an octagonal cross-section tend to have a natural frequency that aligns more closely with the working frequency, making them a preferable choice compared to circular cross-section towers.

7.2 Tower's Deformation

Wind turbine towers can experience angular deflection and displacement because of the loads they endure. These loads primarily stem from the interplay between the rotor blades and the tower structure within the atmospheric boundary layer's flow. Additionally, forces arise due to the routine operation of the turbines, including the rotation of the blades. The top deflection of the tower must not exceed 1% of the total tower height according to ACI 307-98, the estimated result gives wind turbine tower deflection of 0.31m as shown in the next figures, which is below 1% of the tower height. The wind loads on the tower are responsible for these deflection meters.

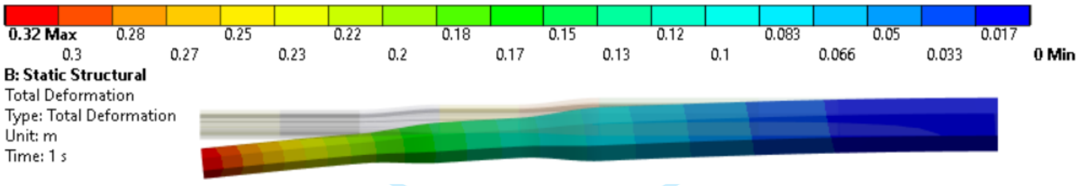

Fig. 8 Total Deformation of Tower

It has been observed that the deformation values in the specific design under investigation are consistently lower than those associated with the circular section towers [1].

7.3 Tower's stresses

The tower's stress limit varies depending on the stage of loading experienced in compression. As per the ACI design code, the limitation of stresses due to design should be less than 21Map compression stresses and 0.24 Map for tension stresses. The results of the stress values determine whether they fall within the stress limitation criteria and whether they are related to compression or tension stresses.

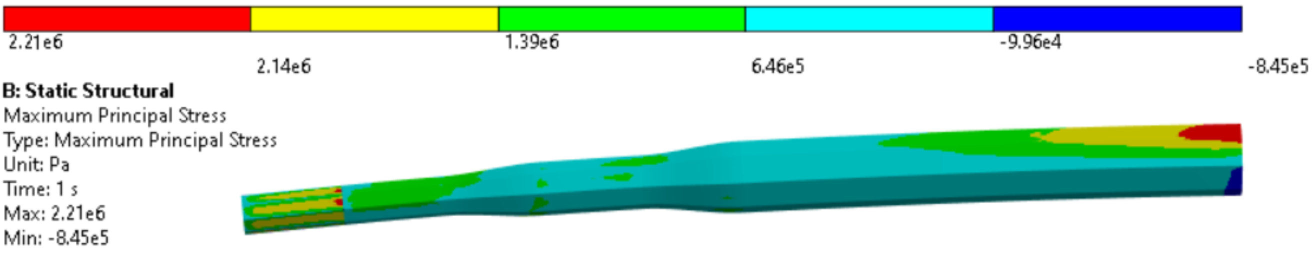

Fig. 9 Stress Distribution along the Tower

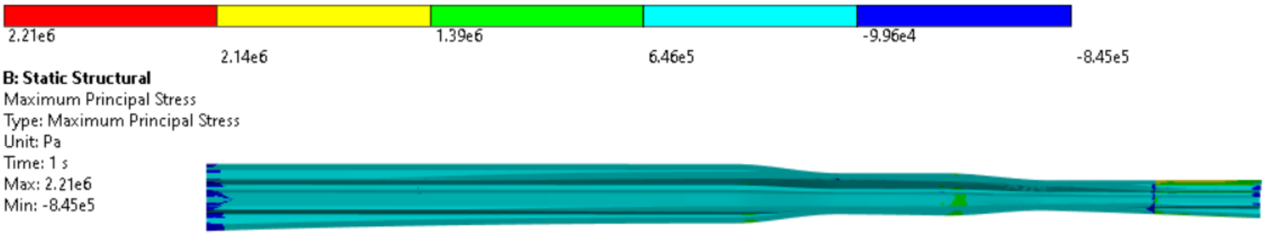

Fig. 10 Section (1) of Stress Distribution along the Tower

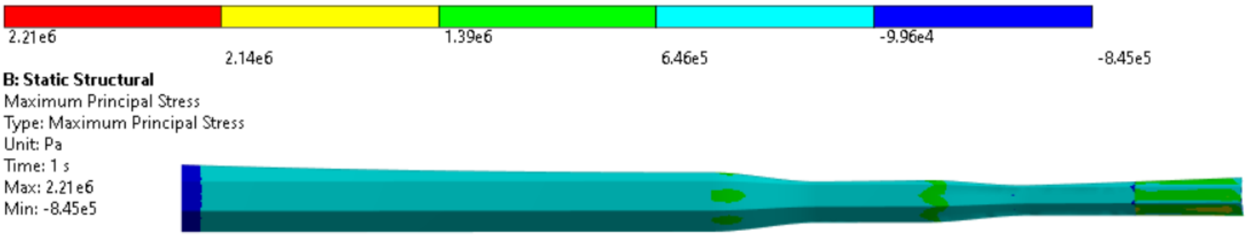

Fig. 11 Section (2) of Stress Distribution along the Tower

To evaluate the effectiveness of the proposed tower design, it was compared to a regular octagonal cross-section [3] and a circular cross-section [1]. The results showed that the proposed cross-section exhibited less stress concentration in the structure, particularly at the corners and notches. This was due to the addition of ribs that were strategically placed to support the areas that are typically subject to high stress. Figure [insert figure number] illustrates the stress distribution of the proposed design, which revealed a maximum compression stress of -8.45 MPa on one side, and a maximum tension stress of 2.21 MPa on another side, as shown in Figures 9, 10, and 11.

Based on the stress results, it has been confirmed that the proposed section is symmetric in all directions, as depicted in Figures 9, 10, and 11. This symmetry is particularly beneficial in areas where the wind direction changes with the time of day and season, enabling better distribution of wind energy and resulting in increased energy production. Furthermore, the symmetry of the section helps reduce vibrations and noise generated by the turbines, thereby increasing their reliability, and reducing the likelihood of malfunctions.

7.4 Buckling of Tower

Structural failure and damage to the turbine can occur due to buckling, making it crucial to take steps to minimize the risk. This can be achieved using high-strength materials, appropriate design, and regular maintenance. By implementing these measures, the turbine tower can remain safe from buckling. The results mentioned the maximum deformation of buckling after 20 cycles due to the limit of the ultimate state is 0.91 m, which falls within the deformation acceptable range.

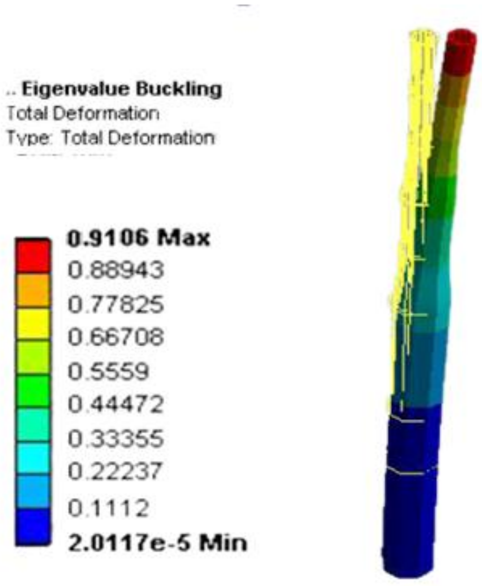

Fig. 12 Buckling of Tower

8. Conclusion

This study aimed to present a model of a 100-meter pre-stressed concrete tower designed to withstand wind loads and support a 3.6 MW wind turbine. It's proposed an innovative octagonal cross-section with internal ribs that enhances its structural integrity. Computational Fluid Dynamics (CFD) analysis and Ansys Workbench Simulation were used to create a 3D Finite Element Method (FEM) model.

This model was utilized to predict performance, evaluate structural integrity, and ensure safety. Throughout the analysis, two scenarios were examined regarding the turbine; the first was its regular operation, where it functioned up to a maximum speed of 35 m/s. The second is considered a failure mode, which occurred when the wind speed reached 59 m/s. In both cases, a thorough assessment was conducted to determine the various forces that affected the tower by using transient analysis. Also, other loads affected by the turbine are considered in this study. These loads were the wind's thrust force and the bending moment of the blades. The effect of wind loads, own weight of the tower, and gravity forces on the supported components are studied too in the research. This study evaluated the performance of a proposed cross-section design for a pre-stressed concrete wind turbine tower compared to traditional cross-sections and regular octagon sections. The proposed system showed less deformation and solved the stress concentration problem by adding internal ribs at the corners. As a result, there were no concentrated stresses at any corners, making it a promising construction option for wind turbine towers.

The proposed tower's natural frequency was 0.49 Hz, which falls within the safe range of 0.22 to 0.66 Hz, thus avoiding resonance. The tower's deformation in normal conditions was less than 55% of the allowable limit. The results also show the values of stress in compression or tension limitations. The turbine model was validated by comparing results with three references [1], [10], and [2]. These references measured a 100m height and a 3.6 MW turbine. The analysis conducted in this manuscript highlights that the new tower cross-section design does not have any stress concentration. Consequently, it can be demonstrated that the proposed system has the potential to be cost-effective, require minimal maintenance, be quickly and easily erected, and have superior aesthetics compared to the predominantly used steel and concrete shaft towers.

References

1. J. A. de Lana, P. A. A. M. Júnior, C. A. Magalhães, A. L. M. A. Magalhães, A. C. de Andrade Junior, and M. S. de Barros Ribeiro, "Behavior study of prestressed concrete wind-turbine tower in circular cross-section," *Eng Struct*, vol. 227, Jan. 2021, doi: 10.1016/j.engstruct.2020.111403.
2. A. Mohammed Abdel-Shakour Hasan and E. Ahmed Badr Eldein Khalil, "Analysis and Design of Optimum Pre-Stressed Concrete Wind Turbine Towers SUBMITTED By Abdelrahman Elsaid Eissa Egypt 2020 A thesis submitted to AASTMT in Partial Fulfillment Of The Requirements for the Award of The Degree of Master's of Sciences in Construction and Building Engineering."
3. H. Ma and R. Meng, "Optimization design of prestressed concrete wind-turbine tower," *Sci China Technol Sci*, vol. 57, no. 2, pp. 414–422, 2014, doi: 10.1007/s11431-013-5442-8.
4. I. Lotfy, "Prestressed Concrete Wind Turbine Supporting System." [Online]. Available: https://digitalcommons.unl.edu/civilengdiss/45
5. E. Wu *et al.*, "Wind Load Evaluation of Wind Turbine Tower Design," in *Journal of Physics: Conference Series*, IOP Publishing Ltd, Sep. 2020. doi: 10.1088/1742-6596/1622/1/012071.
6. S. Adhikari and S. Bhattacharya, "Dynamic analysis of wind turbine towers on flexible foundations," *Shock and Vibration*, vol. 19, no. 1, pp. 37–56, 2012, doi: 10.3233/SAV-2012-0615.
7. H. Ma and R. Meng, "Optimization design of prestressed concrete wind-turbine tower," *Sci China Technol Sci*, vol. 57, no. 2, pp. 414–422, 2014, doi: 10.1007/s11431-013-5442-8.
8. F. Ferroudji, "Numerical modal analysis of an 850 KW wind turbine steel tower," *International Review of Applied Sciences and Engineering*, vol. 12, no. 1, pp. 10–18, Apr. 2021, doi: 10.1556/1848.2020.00091.
9. M. W. Lanier, "LWST Phase I Project Conceptual Design Study: Evaluation of Design and Construction Approaches for Economical Hybrid Steel/Concrete Wind Turbine Towers; June 28, 2002 -- July 31, 2004," 2005. [Online]. Available: http://www.osti.gov/bridge
10. A. E. Eissa, M. Abdel, S. Hasan, and E. Khalil, "MODAL ANALYSIS OF PRESTRESSED CONCRETE WIND TURBINE TOWER", doi: 10.24327/ijrsr.2020.1101.5013.
11. F. Ferroudji, "Numerical modal analysis of an 850 KW wind turbine steel tower," *International Review of Applied Sciences and Engineering*, vol. 12, no. 1, pp. 10–18, Apr. 2021, doi: 10.1556/1848.2020.00091.
12. M. AbuGazia, A. A. El Damatty, K. Dai, W. Lu, and A. Ibrahim, "Numerical model for analysis of wind turbines under tornadoes," *Eng Struct*, vol. 223, Nov. 2020, doi: 10.1016/j.engstruct.2020.111157.
13. M. W. Lanier, "LWST Phase I Project Conceptual Design Study: Evaluation of Design and Construction Approaches for Economical Hybrid Steel/Concrete Wind Turbine Towers; June 28, 2002 -- July 31, 2004," 2005. [Online]. Available: http://www.osti.gov/bridge
14. S. Yoshida, "WIND ENGINEERING VOLUME," 2006.
15. *Taek, H. Han, G.-L. Yoon, J.-H. Yi, and D. Won, "Design feasibility of double-skinned composite tubular wind turbine tower." [Online]. Available: http://galleryhip.com;

16. J. C. Nicholson, “Design of wind turbine tower and foundation systems,” University of Iowa, 2011. doi: 10.17077/etd.bhnu76gr.
17. R. Levy and O. E. Lev, “RECENT DEVELOPMENTS IN STRUCTURAL OPTIMIZATION 3.”
18. E. Wu *et al.*, “Wind Load Evaluation of Wind Turbine Tower Design,” in *Journal of Physics: Conference Series*, IOP Publishing Ltd, Sep. 2020. doi: 10.1088/1742-6596/1622/1/012071.
19. Y. Li, W. Liang, E. Xiong, and J. Zhao, “Design and numerical simulation of timberwork wind power generation tower model,” in *Applied Mechanics and Materials*, 2011, pp. 3529–3534. doi: 10.4028/www.scientific.net/AMM.71-78.3529.
20. S. Sahin, “Wind Turbine Tower Structure Analysis According to Wind Load in Terms of Cost ‘EMSHIP’ Erasmus Mundus Master Course in ‘Integrated Advanced Ship Design.’”
21. S. Yoshida, “WIND ENGINEERING VOLUME,” 2006.
22. M. A. Asareh, W. Schonberg, and J. Volz, “Effects of seismic and aerodynamic load interaction on the structural dynamic response of multi-megawatt utility-scale horizontal axis wind turbines,” *Renew Energy*, vol. 86, pp. 49–58, Jul. 2015, doi: 10.1016/j.renene.2015.07.098.
23. J. C. Nicholson, “DESIGN OF WIND TURBINE TOWER AND FOUNDATION SYSTEMS: OPTIMIZATION APPROACH,” 2011.
24. British Standards Institution., *Wind turbines. Part 2, Design requirements for small wind turbines*. BSI, 2006.
25. A. N. Singh, “Point of View Concrete construction for wind energy towers,” 2007.
26. E. Hernandez-Estrada *et al.*, “Considerations for the structural analysis and design of wind turbine towers: A review,” *Renewable and Sustainable Energy Reviews*, vol. 137. Elsevier Ltd, Mar. 01, 2021. doi: 10.1016/j.rser.2020.110447.
27. T. Hyun Gwon, “Structural Analyses of Wind Turbine Tower for 3 kW Horizontal-Axis Wind Turbine,” 2011.
28. “3 MW PLATFORM POWERFUL AND EFFICIENT GE Renewable Energy.” [Online]. Available: www.ge.com/renewableenergy
29. “NONLINEAR DYNAMIC ANALYSIS OF WIND TURBINE TOWERS SUBJECT TO DESIGN WIND AND SEISMIC LOADS by Muhsen Awad Sassi.”
30. A. Berghuvud and Dipl.-I. M. Goudarzi, “3D Simulation of a 5MW Wind Turbine.”
31. E. Hernandez-Estrada *et al.*, “Considerations for the structural analysis and design of wind turbine towers: A review,” *Renewable and Sustainable Energy Reviews*, vol. 137. Elsevier Ltd, Mar. 01, 2021. doi: 10.1016/j.rser.2020.110447.
32. H. M. Negm and K. Y. Maalawi, “Structural design optimization of wind turbine towers.” [Online]. Available: www.elsevier.com/locate/compstruc
33. V. Valamanesh and A. T. Myers, “Aerodynamic Damping and Seismic Response of Horizontal Axis Wind Turbine Towers,” *Journal of Structural Engineering*, vol. 140, no. 11, Nov. 2014, doi: 10.1061/(asce)st.1943-541x.0001018.
34. J. C. Nicholson, J. S. Arora, D. Goyal, and J. M. Tinjum, “0 th World Congress on Structural and Multidisciplinary Optimization Multi-Objective Structural Optimization of Wind Turbine Tower and Foundation Systems using Insight: A Process Automation and Design Exploration Software.”
35. M. Muskulus and S. Schafhirt, “Design Optimization of Wind Turbine Support Structures-A Review,” 2014. [Online]. Available: http://www.isope.org/publications
36. S. Sritharan, “Wind turbine towers: Precast concrete Hexcrete may help increase renewable energy capacity with taller hub heights,” *PCI Journal*, vol. 60, no. 6, pp. 33–38, 2015, doi: 10.15554/pcij60.6-01.
37. “HEUROPEaNNION,” vol. 1, no. 2005, 2011.
38. B. Leander, A. Čaušević, and H. Hansson, “Applicability of the IEC 62443 standard in Industry 4.0/IIoT,” in *Proceedings of the 14th International Conference on Availability, Reliability and Security*, 2019, pp. 1–8.
39. A. C. Way and G. P. A. G. Van Zijl, “A study on the design and material costs of tall wind turbine towers in South Africa,” *Journal of the South African Institution of Civil Engineering*, vol. 57, no. 4, pp. 45–54, 2015, doi: 10.17159/2309-8775/2015/v57n4a6.
40. B. Kuhn, J. Marquis, and H. Rotatori, “Wind turbine design and implementation,” 2010.
41. C. S. Butterfield, “Using partial safety factors in wind turbine design and testing. NREL/CP-440-23257,” no. September, p. 12, 1997.
42. N. Namura, “Wind shear estimation model using load measurement of wind turbine tower and surrogate model,” *Wind Energy*, vol. 23, no. 2, pp. 327–339, 2020.
43. E. N. Materia and D. E. P. Pct, “WO 2009/056898 Al (81),” no. 12, 2009.
44. R. Peggar, S. Sritharan, P. Sarkar, J. Matthew, R. H. David, and J. F. Peters, “Design and structural testing of tall Hexcrete wind turbine towers,” 2017, [Online]. Available: https://lib.dr.iastate.edu/etd
45. R. Wass, “Design of Wind Turbine Tower Height and Blade Length: an Optimization Approach,” p. 72, 2018, [Online]. Available: http://scholarworks.uark.edu/meeguhthttp://scholarworks.uark.edu/meeguht/70

46. S. Karmouche and A. Bentamy, “School of Science and Engineering Tower Design and Analysis for a Small Wind Turbine,” pp. 0–42, 2016, [Online]. Available: http://www.aui.ma/sse-capstone-repository/pdf/spring2016/Tower Design And Analysis For A Small Wind Turbine.pdf
47. S. Sahin, “Wind Turbine Tower Structure Analysis According to Wind Load in Terms of Cost,” no. February 2016, pp. 1–146, 2009.
48. G. N. Milan Veljkovic, Christine Heistermann, Marko Pavlovic Markus Feldmann, Daniel Pak, Carl Richter, Carlos Rebelo, Paulo Pinto, Rui Matos, Charalampos Baniotopoulos, Michaela Gkantou, Veronique Dehan, “High-Strength Steel Tower for Wind Turbines (HISTWIN _ Plus),” p. 141, 2014, [Online]. Available: http://www.winercost.com/cost_files/HISTWIN_Plus_Report.pdf