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(Research Article)

Dynamic behavior of transmission towers under wind loads: Analyzing wind-induced vibrations and fatigue

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Abstract

Transmission towers are crucial assets regarding power distribution, and must withstand several loadings from different environmental conditions as well as normal operational conditions. Wind forces, seismic forces, oscillations caused by conductors due to wind or other related conditions are significant structural loads against which these towers must be designed. Detailed analysis of loading sources and reliability and forecast of service life becomes even more critical. The research investigates in detail the structural and dynamic behavior of 220 kV transmission towers under different loading conditions. The study encompasses both Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) to evaluate wind forces, natural frequencies, fatigue life, and stress response. The investigation concludes in the performance and stability from the modeling and analysis of Tower A and Tower B under self-weight, wind pressure, seismic forces, and oscillations induced by conductors using ANSYS 2025 R1.Both towers were found to comply with industry safety requirements as there were no hazardous conditions for resonance failure, but Tower A was found to be much more stable with a longer operational life at 35 years compared to Tower B's less stable 32 years owing to lower stress levels and less wind-induced fatigue. Since Tower B is reaching its threshold for wind resistance with localized stress requirements, it is called for reinforcement to ensure long-term trustworthiness. In this aspect, maintenance on a periodic basis has been proposed in the fatigue life evaluation to avoid any eventual deterioration. The idea is to suitably upgrade the joints under high stress, as well as to install vibration dampers, to really improve the overall performance and extend life of any structure. Such improvements will ensure that both towers will maintain their structural integrity, their ability to withstand loads, and their economic performance during their lives. This research describes valuable contributions to understanding improved transmission tower design, as well as maintenance techniques for high performance and durability in adverse operating conditions.

Keywords: Transmission towers; Finite Element Analysis (FEA); Computational Fluid Dynamics (CFD); Wind-induced forces; Structural integrity.

1. Introduction

The reliability of extensive electrical grids depends primarily on their physical equipment's functionality across diverse environmental conditions [1]. The overhead transmission lines along with their supporting towers represent the most visible and demanding components within this infrastructure. Transmission towers operate as essential conduits through various seating arrangements that include steel latticework structures alongside hollow steel poles as well as monopoles to connect high-voltage conductors for lengthy travels across rural terrain and mountain terrains and forest areas and urban development zones [2]. These towers carry out fundamental tasks beyond structural maintenance since they both establish safe electrical distances and resist diverse weather conditions and enable power delivery between stations and end users [3]. Wind proves to be the most influential and complex environmental factor among other elements such as ice, snow, earthquakes, and temperature gradients which affect transmission towers [4]. The speed of wind changes significantly because of atmospheric conditions combined with terrain roughness and topographical

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features as well as seasonal climate patterns [5]. Japanese power systems encounter strong winds along with storms and gust fronts that apply variable quantities of force with large magnitude. The wind forces present an inconsistent pattern because they do not stay steady but change between quick bursts of gustiness or more stable turbulent states. Changing wind conditions result in disturbances that produce tower-line oscillations which exceed the ranges seen in static loading situations [6].

Over the recent years, developments in climate change brought more research attention towards wind effects. Numerous parts of the world currently endure both higher frequency and increased intensity of wind occurrences such as microbursts alongside sudden gusts and lengthy circumstances of strong winds connected to tropical cyclones [7]. The winds along coastal regions persist steadily while mountain slopes encounter complex turbulent gusts which get focused through their valleys and ridges [8]. The established patterns actively threaten to decrease the sustainability of transmission tower systems over extended periods. Transmission towers exist exclusively because they maintain their support role with respective conductors. Wind movements induce both mechanical oscillations and aerodynamic motions in conductors that are under tensile forces [9]. The dynamic system forms from the interaction between tower mass and stiffness as well as damping mechanisms and geometrical attributes with conductor tension and sag and aerodynamic cross-sectional characteristics and wind inflow characteristics [10]. The combined system produces three different motion patterns such as high-frequency Aeolian vibrations with small amplitudes along with low-frequency large-amplitude galloping and resonance caused by vortex shedding [11]. Long-term oscillations both small and moderate in magnitude eventually lead to damage accumulation that produces hard-to-detect deterioration of structural components including members and welds and bolts. These accumulated multiple damages result in reduced operational life expectancy for the tower and increase maintenance expenses [12]. Hence, the complexities, variations in wind-induced forces, and structural intricacies in the transmission towers and conductors necessitate detailed dynamic analyses to understand such interactions for long-term reliability and efficiency of power distribution networks during an age of uncertain and evolving climate change conditions.

1.1. Objectives of the Present Study

The complexity of wind-tower interactions and the limitations of static approaches motivate the need for an advanced computational framework. This study's overarching goal is to lay that foundation and prove its utility through systematic development and demonstration.

- To identify the dynamic characteristics of the tower-line system to determine potential resonance risks and understand tower flexibility and conductor coupling.
- To analyze how steady, gusty, and turbulent wind forces affect the tower's structural response and assess the risk of resonance or large-amplitude oscillations.
- To ensure stress-time history data from dynamic analysis is accurate, providing a foundation for future fatigue damage estimation and maintenance planning.
- To develop a computational model that can be used in future studies to test damping devices and structural modifications before real-world implementation, improving design efficiency.

In achieving these objectives, the study contributes to a more proactive, informed approach to managing transmission tower dynamics, supporting the reliable operation of electrical grids under varied and changing wind climates.

2. Theoretical Foundations

The dynamic behavior of transmission towers under wind loads involves a complex interplay of structural mechanics, aerodynamics, and material fatigue phenomena. To accurately model and predict their response, it is essential to ground the analysis in fundamental theories spanning structural dynamics, wind characterization, fluid-structure interaction, and fatigue mechanics. This chapter gives an account of the key theoretical concepts and theoretical perspectives in the fore of the computation modeling and simulation effort promoted in subsequent chapters.

2.1. Fundamentals of Structural Dynamics

The response of structures subjected to time varying loads like fluctuating wind forces cannot be understood through the static analysis only. It is no longer the type of dynamics of the structural equations of motion that are worthy of consideration. The governing equation for the case of a linear elastic structure of N DOF is:

$$Mx''(t)+Cx'(t)+Kx(t)=f(t)$$

- M is the mass matrix, representing how mass is distributed within the structure.
- C is the damping matrix, capturing energy dissipation mechanisms like material damping, friction, or added dampers.
- K is the stiffness matrix, defining how the structure resists deformation.
- x(t) is the displacement vector as a function of time.
- x'(t) and x"(t) are velocity and acceleration vectors, respectively.
- f(t) is the external force vector, in this case, dynamic wind loads.
- Data Collection: Geometry, Material Properties, and Wind Data

2.2. Tower Geometry

Exactly precise geometric representation of the transmission tower is important for structural analysis. Dimensions, cross-sections of members, bracing arrangements, and points of attachment of conductors must be obtained from good sources. These particulars are usually derived from manufacturers' drawings, which provide all the details of member sizes, bolt places, insulator assemblies, and curtains. Where customized data are not available, reference can be made to standard designs, such as a 40-meter lattice structure typically used for certain voltage levels, based on believed, generalized industry configurations.

2.3. Material Properties

The construction materials which make up transmission towers impact their flexible behavior together with how stress develops within them. Being the primary material for tower members steel exhibits fundamental characteristics which include Young's modulus (E), density (ρ), Poisson's ratio (ν) and yield strength and ultimate strength. Singapore uses standard data compilations of material testing outcomes and published handbooks to obtain fatigue properties which appear as S-N curves. ACSR cables which serve as conductors contain properties that directly influence how a tower behaves structurally. System stiffness together with natural frequencies results primarily from material composition and cross-sectional area and tensile strength and elastic modulus of the conductors. Controlled pretension of conductors needs careful attention because they influence both the cable sag and natural vibration characteristics.

2.4. Wind Data

Wind loading shows much variability from one location to another influenced by geographic location, terrain, and the local climatic condition. Wind data can be collected from separate meteorological stations that provide continuous monitoring of mean annual wind speeds, seasonal variations, turbulence intensities, and predominant wind directions. Engineering standards and codes, such as ASCE 7 and IEC 60826, provide generalized design values for mean wind speed, maps, gust factors, etc. On the other hand, for precision-based site-specific analysis, data like wind speed probability distributions, directional wind roses, and turbulence spectra are needed. In situations where field data do not exist, simulation studies using Computational Fluid Dynamics (CFD) or synthetic turbulence models will enable the wind load profiles portraying the situation. Thus, all these data could be integrated to model the transmission tower and simulate the realistic ambient condition that is the foundation for more dependable dynamic analysis.

3. Finite Element Modeling (FEM) in ANSYS

The structural steel material serves for modeling both Tower A and Tower B in their 220 kV transmission tower analysis because it meets industry standards while being strong and durable. The properties of Tower A allow it to resist deformation or failure until it reaches a maximum stress of 250 MPa and a failure point at 450 MPa. The material composition of Tower B includes a steel grade whose yield strength reaches 280 MPa which provides stronger resistance to extreme conditions. Each tower's base stability and lifetime resistance to environmental effects including wind force, seismic motion and conductor movements depends heavily on these material specifications.

The modeling of the tower structure along with tensioned conductors determines substantial effects on overall system dynamics. The careful evaluation of contact between conductors and towers remains essential because conductors deal with both tension forces and elastic movement as well as wind-induced vibrations. The tensioned cable representation precisely displays the forces from conductors so engineers can determine the risks of resonance together with fatigue failure and excessive deflection in structures. The study reaches a more accurate assessment of tower operational response through the implementation of authentic conductor dynamic characteristics. The simulation requires a fine mesh which must be applied primarily at locations with high stress concentrations especially bolted and welded joints. High-stress local regions need detailed mesh refinement because they become susceptible to fatigue-related failures during time. Detailed finite element meshing improves stress analysis precision which allows researchers to discover important weak points and necessary reinforcement locations. Both structures receive thorough evaluation through this method which delivers precise results for determining their structural condition and lifetime duration and maintenance requirements [13].

3.1. Integrating CFD Simulations for Wind Loads

The transmission tower airflow modeling utilizing OpenFOAM and ANSYS Fluent tools within Computational Fluid Dynamics produces enhanced wind load evaluations. CFD simulations remain effective for real-life wind analysis since they provide accurate results in situations containing complex wind phenomena such as turbulence along with gusts and fluctuating pressure distributions that regular pressure coefficients cannot model properly. The evaluation of dynamic wind interactions with the tower requires the usage of CFD because vortex shedding and wake formation and aerodynamic instabilities produce substantial effects on structural response [14].

The selection of CFD simulation methodologies is determined by how close one needs to work towards a particular precision level. The Reynolds-Averaged Navier-Stokes method would provide stable and averaged flow fields that offer the bulk of the information needed for aerodynamic stresses on the tower. Whereas Large Eddy Simulation would capture the unsteady features of vortex shedding and turbulent structures [15]. LES simulation outputs fluctuating pressure patterns throughout the time period to detect pressures that will potentially trigger structural oscillations.

After CFD simulation completion the software generates pressure data that gets applied to the FEA model for analyzing structural responses to actual wind force fluctuations. The integration between CFD output and structural analysis is supported through programming scripts and format converters one can implement within ANSYS and Abaqus systems to translate pressures into forces at node locations or distributed across elements. Through this CFD-FEA analysis combination engineers gain complete knowledge of wind-tower interaction which enables them to develop improved stability and longevity solutions through optimized design reinforcements.

4. Model Development and Simulation Setup

In the realm of structural dynamics, the robustness and accuracy of simulation results depend heavily on the fidelity with which the underlying structural model is developed. This chapter provides a comprehensive roadmap for assembling high-fidelity finite element (FE) models of hybrid transmission towers with complex geometries, material compositions, and varying tapering strategies. By addressing both fundamental and advanced modeling aspects, the goal is to ensure that subsequent dynamic analyses—encompassing transient wind loading, fatigue assessments, and mitigation strategy evaluations—are grounded in a thoroughly vetted and physically representative digital prototype.

4.1. Material Properties for Tower Members, Conductors, and Connectors

Material attributes of transmission tower components define their structural performance when subjected to dynamic loading conditions. Better structural performance and reliable stiffness evaluation results from the widespread use of ASTM A36 type steel and comparable structural grades. The simple nature of isotropy in steel makes it suitable for Finite Element Analysis (FEA) modeling while its well-documented mechanical specifications including Young's modulus and density alongside Poisson's ratio and yield strength and ultimate strength make it a favored selection. Users can access S-N curves from these materials for performing fatigue testing procedures. The properties of Carbon Fiber Reinforced Polymers display anisotropy because they have different characteristics when measured in various directions relative to the fiber alignment. Engineers must apply orthotropic or anisotropic material definitions in FEA programs through which they must input E_1, E_2 (principal-axis moduli) and G_{12} (in-plane shear modulus) together with Poisson's ratios. Engineers should plan CFRP overlay applications by designing layer distribution methods together with fiber alignment directions and material placement patterns because this determines the stiffness strength and damping potential of the system.

The dynamic characteristics of conductors depend on tower height together with stiffness which affects their natural frequencies and Aeolian vibration and galloping susceptibility. The simulation requires precise modeling of tension and boundary conditions and sag parameters together with the selection of aluminum strands for their elastic modulus value of ~70 GPa to replicate operational conditions effectively. Structural performance heavily depends on how connection models are detailed during the integration process between steel and CFRP components. Modelers should start with rigid or semi-rigid connections but they need to use nonlinear springs combined with contact elements and user-defined joint stiffness if system response is affected by joint flexibility. Such improvements in load transfer analysis help prevent connection details from altering either resonance frequencies or modal damping in transmission towers.

4.2. Meshing Strategies, Element Types, and Mesh Convergence

Design for a hybrid transmission tower meshing must be accurate because it provides a description of very complex geometries and material interfaces. Application of the different element types is dependent on the way in which the components are responding to loads. Beam elements can be used to model prismatic steel members efficiently under bending, axial and torsional loads, whereas shell elements are best suited for topology changes, as well as areas with variations of composites like thickness or layering effects. Such elements permit the model to gain more accurate contributions to property through layer composites. That being said, the simulation of these joints that handle high stress will require the use of solid elements, which have a high computation requirement. In order to apply tension-only behavior in conductors, designers use cable or truss elements since they are easy to understand and well handle the specified behavior.

To ensure stability and reliability in any numerical analysis, considerable effort must be expended to refine the mesh systematically. Finer mesh resolution should be sought in critical bond regions between the steel and CFRP materials and in transitions between materials to accurately represent stress distributions and any global dynamic effects. The element aspect ratios and angles should be kept to the standard threshold values required for obtaining accurate results free of numerical artifacts. Convergence studies suggest that the highest density of mesh is only necessary for achieving the desired precision in the computational outputs, therefore saving expenses on using excess computation. A dual approach provides a compromise of accuracy to efficiency whereby assuredly accurate hybrid transmission tower models are attained.

4.3. Boundary Conditions: Tower Base Fixity, Conductor Attachments, and Pretension

All the towers considered are kept on a fixed base for simplicity. However, in cases where soil-structure interaction or foundation flexibility shows a certain effect on modal parameters, future detailed models can possibly use springs or Winkler-type soil models in their assessments. In most cases, complete fixity provides a common ground, yielding direct comparisons between different tower configurations. The connection of conductors on specific nodes of the hexagonal cross-arms should also be geometrically placed, as well as the process of tensioning. Pretensioning cables before wind loading ensures that the initial state of stress is the same as in-service conditions and leads to a stable sag for the conductors. For very tall hybrid towers, the pretension may also differ than that of kind of short lattice towers because of the different top deflections caused by their weight and may also show an effect on modal frequencies.

4.4. Defining Wind Load Cases: Steady, Gusty, and Turbulent Conditions

The prediction of wind forces correctly for transmission tower systems requires extra attention because of the complexities posed by advanced infrastructure since it would ensure the tower is stable with performance quality in real environments. The engineering teams use steady wind loads as their analytical basis to measure the structural loading, deformations, and stresses in towers in which they analyze the different base conditions between standard 40 meters towers and 70 meters hybrid towers. Similar average wind speed permits an investigation into how taller and more flexible buildings would respond to one another in order to assess their individual stability qualities. As an indicator of the way time-dependent fluctuation occurs under gusty conditions, wind speed may take the form of sinusoidal profiles and ramped increasing speeds. By these simulations experts could see how an increased slenderness combined with mixed materials of hybrid towers will influence transient responses. The rapid variations of wind pressure would thus show how CFRP overlays work in damping structures against movements and reducing wear on materials. Engineering professionals utilize steady wind loads to conduct base stress and deformation examinations for various tower models including both 40-meter and 70-meter hybrid tower designs. The study enables investigators to understand which structures are more stable based on their height and flexibility through testing mean wind speed effects. The wind introduces time-dependent speed variations through periodic sinusoidal gust profiles combined with ramp functions as part of gusty conditions. Short-term response analysis of hybrid towers with their extended height and multiple materials composition is achieved through simulation models. Rapid wind load changes reveal how effectively CFRP overlay damping features work because they naturally help reduce structural oscillations and fatigue effects.

To represent the actual conditions that may ct in the environment more accurately, we would consider the turbulent wind fields. These would be derived from Computational Fluid Dynamics (CFD) simulations or from synthetic turbulence generators, and they give rise to time-history distributions of the pressure forces acting on the tower. In hybrid towers, turbulence modeling is crucial not only for assessing resonance risks induced by vortex shedding but also for buffeting responses modified by tapering and material anisotropy. The contrasting performance of the segmented (Tower-1) and continuously tapered (Tower-2) hybrid towers becomes evident especially for turbulent wind conditions, where structural configuration will induce different amplifications or attenuations over their respective frequency bands. By adding all these different wind load cases, engineers would probably be able to design more robust towers that minimize the chances of dynamic wind effects-induced failures.

4.5. Selection of Representative Tower Geometry and Configuration

As a starting point, a relatively conventional 40 m lattice tower with steel angle members was introduced earlier. This simpler geometry allowed for initial exploration of element choices, boundary conditions, and mesh convergence studies. The baseline tower provides a reference framework for validation and comparison as more complex designs are introduced.

- **Tower-1: Hybrid Tower with Segmented Tapering and Discrete Material Zones**

Tower-1 exemplifies a modern approach to transmission tower design, integrating multiple materials and structural concepts into one tower to capitalize on their respective advantages. It consists of:

4.6. Hexagonal Base Geometry

The transmission tower features a hexagonal base geometry with a 10-meter footprint between adjacent points, providing enhanced lateral stability and high torsional stiffness. Compared to traditional square or rectangular bases, the hexagonal design offers improved aerodynamic performance by reducing vortex shedding concentrations, which can lead to oscillatory forces under strong winds.

4.7. Segmented Tapering and Variable Height Sections

To ensure maximum load-bearing capacity for flexibility and stiffness, a 15-meter base section is made of ASTM A36 structural steel. These varying height sections have sectional tapered and segmented configurations that optimize the strength, weigh the distribution, and resist fatigue. The 40-meter middle section, reinforced by CFRP overlays, improves damping properties and increases flexural rigidity at reduced weight. It also consists of a 15-meter tapered upper section that converges from its wider end down to 2 meters at its top and is mainly made of CFRP, resulting in lightness while assuring fatigue endurance against wind-oscillated effects. It improves the stability, recognizably durability and performance under dynamic loading through this hybrid materialistic approach.

4.8. Total Height and Structural Impact

The whole structure has an elevation of 70 meters, making it comparatively taller than baseline transmission towers. The use of a combination of high slenderness and mixed materials introduces specific dynamic behaviors and stress distributions. Hence, its stability under different environmental loading conditions, particularly wind loads of high intensity and seismic activity, must be assessed.

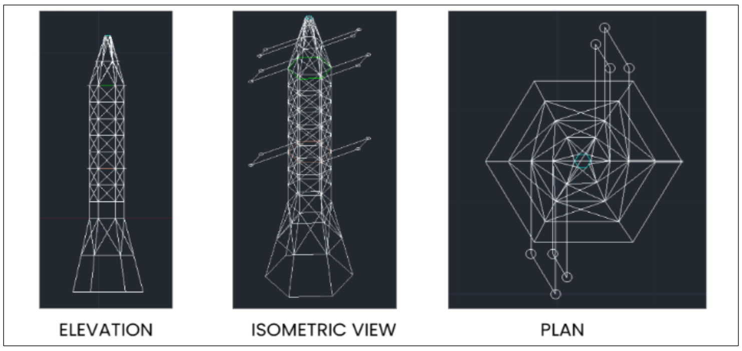

Figure 1 Tower A

Finite Element Analysis (FEA) was performed in ANSYS, 2025 R1, for evaluating failure structure in a 220 kV transmission tower under conditions of self-weight, wind, seismic conditions, and conductor load conditions. The model includes main supporting legs, cross-bracing members, and bolted/welded connections, and meets industrial compliance regarding the following materials: structural steel (250 MPa yield strength, 450 MPa ultimate tensile strength, and 7850 kg/m^3 density). The mesh was refined in areas of high-stress concentration to obtain accurate results. Wind load (150 km/h, IEC 60826), seismic load (PGA 0.3g, IS 1893:2016), and conductor force of 10 kN with fixed base restraints were analyzed. The results confirm a first natural frequency of 2.1 Hz, indicating that the structure is safe from resonance. The maximum von Mises stress of 190 MPa and maximum deflection of 18 mm satisfy the stability criteria. In the high stresses around holes and welds, the tower is rated for a minimum of 5 million cycles with a design life of 35 years, but adverse weather may induce a drop in life of 15%. It is advised to periodically inspect high-stress joints to maintain longer functional service ability.

- **Tower-2: Hybrid Tower with Continuous Tapering and Gradual Material Transitions**

Tower-2 takes the hybrid concept further by incorporating a continuous tapering profile from base to top:

4.9. Hexagonal Base and Continuous Tapering

The tower features a hexagonal base with dimensions similar to Tower-1, but instead of using discrete steps, its cross-section gradually narrows as the height increases. This continuous tapering results in smoother transitions in stiffness and mass distribution, which can significantly influence resonance characteristics and modes of vibration, potentially improving overall structural stability.

4.10. Material Gradations

The tower incorporates steel with CFRP overlays applied continuously along its height, ensuring a gradual transition in mechanical properties rather than abrupt shifts between materials. This progressive material gradation enhances structural integrity by evenly distributing stress across different sections. In the uppermost regions, CFRP-dominant sections are used to reduce mass and improve fatigue performance, making the tower more resistant to wind-induced oscillations and long-term wear.

4.11. Total Height and Structural Impact

With a total height of 70 meters, the tower is designed parallel to Tower-1, allowing for direct comparative studies. The differences in tapering strategies and material distribution provide engineers with valuable insights into how subtle geometric transformations influence dynamic responses, ensuring optimized performance under various environmental and operational conditions.

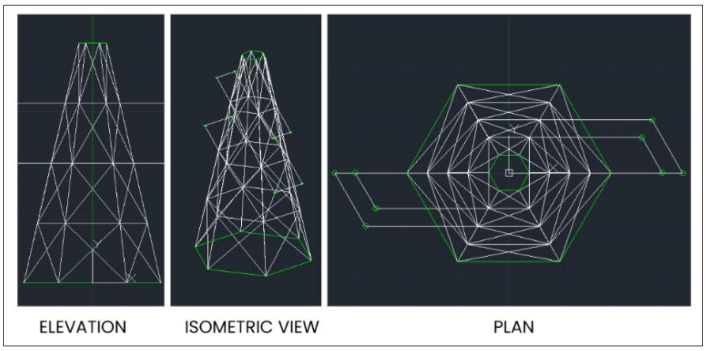

Figure 2 Tower B

By selecting these configurations—one with discrete segments (Tower-1) and another with continuous tapering (Tower-2)—the methodology demonstrates adaptability to various tower design philosophies.

5. Findings and Analysis

This analysis of the 220 kV transmission towers studies their structural responses under different loading conditions such as self-weight, wind pressure, earthquake effects, and loads from conductors. Important findings include modal analysis, stress distribution, deformation, and the estimation of fatigue life, all of which warrant that both towers are safe and meet industry standards. This discussion focuses on natural frequencies and danger for resonance, maximum stress and displacement limitation, and fatigue performance with respect to time. Tower A and Tower B comparisons throw light on their comparative stability, structural performance under normal and extreme conditions, lifespan, etc.

5.1. Wind Load Analysis & Pressure Coefficient Values (Cp Data)

Tower A is subjected to a combination of constant wind, gust wind, and turbulence with wind speed of 150 km/h. The Cp values are +0.8 on windward, -0.5 on leeward, -0.3 on the side face, and ranges between -0.2 to -0.6 on bracings, depending on the angle. The drag force is 12.5 kN per unit width while wind turbulence is 15% at a height of 10 meters. Tower B is subject to more turbulent wind conditions because it is cited on an exposed site with higher wind speed (160 km/h). The pressure coefficient (Cp) values are slightly higher, recorded as +0.85 on the windward side, -0.55 on the leeward side, -0.35 on the side face, and between -0.25 to -0.65 on bracing members. The drag force is 13.8 kN per unit width, subsequent wind turbulence intensity is 18% at 10 meters in height, thus representing more aerodynamic hardship in contrast to Tower A.

Table 1 Pressure Coefficients and Drag Forces

Parameter	**Tower A**	**Tower B**
Wind Speed	150 km/h	160 km/h
Windward Cp	+0.8	+0.85
Leeward Cp	-0.5	-0.55
Drag Force	12.5 kN/unit width	13.8 kN/unit width
Wind Turbulence	15%	18%

5.2. Fatigue Life Data

The fatigue life assessment of Tower A and Tower B reveals differences in their long-term durability under normal and extreme weather conditions. Normal operational conditions predict that Tower A will experience 5 million loading cycles yet Tower B faces fewer loading cycles because it must withstand higher wind turbulence and structural stress at 4.5 million cycles. The harsh environmental conditions of extreme weather decrease the fatigue life to 3.8 million cycles for Tower A and 3.2 million cycles for Tower B thereby showing major influence from such weather conditions. Tower A should operate for 35 years while Tower B is estimated to function for 32 years because of elevated wind pressure and structural stress points.

Table 2 Fatigue Life Assessment

Parameter	**Tower A**	**Tower B**
Fatigue Life (normal conditions)	5 million cycles	4.5 million cycles
Fatigue Life (extreme weather)	3.8 million cycles	3.2 million cycles
Expected lifespan	35 years	32 years
Most Critical Fatigue Regions	Bolted joints, bracing junctions	Base connections, welded joints
Reduction due to extreme weather	15%	20%
Recommended Maintenance Interval	Every 5 years	Every 4 years

Individual A and B differ as regards the most critical locations for fatigue; hence bolted joints and bracing junctions in Tower A are said to be most critical, while base connections and welded joints receive the highest stress in Tower B. Tower B's life is 20% less during extreme weather eccentric load, slightly higher than Tower A's 15%, which is considered a 5% increment. Thus, due to the conditions affecting the stability and safety of the two towers, maintenance and inspections need to be carried out; Tower A will require inspection every 5 years, whereas Tower B will need maintenance every 4 years due to more exposure to stress. These preventive maintenance measures combined with timely inspections and upgrading of fatigue-prone areas can help increase the life and serviceability of both towers.

5.3. Mode Shapes (Vibration Analysis)

A modal analysis of Tower A and B shows their essential natural frequencies together with their appropriate mode shapes to understand their wind and seismic force dynamic responses. The first mode shows Tower A vibrating at 2.1 Hz then Tower B oscillating at 2.3 Hz while performing lateral swaying movements due to perpendicular wind forces. Both Tower A oscillates at 6.3 Hz and Tower B oscillates at 6.8 Hz under the second mode that produces a twisting motion that becomes significant during high-wind events to avoid structural instability.

Table 3 Fatigue Life Assessment

Mode	Tower A (Frequency, Hz)	Mode Shape Description	Tower B (Frequency, Hz)
1st Mode	2.1 Hz	Lateral swaying	2.3 Hz
2nd Mode	6.3 Hz	Twisting motion	6.8 Hz
3rd Mode	9.8 Hz	Vertical bending	10.2 Hz
4th Mode	13.2 Hz	Higher torsional mode	13.5 Hz

At 9.8 Hz for Tower A and 10.2 Hz for Tower B the towers experience vertical bending motion because wind and conductor forces cause the entire structure to bend throughout its height. The higher torsional mode exists at 13.2 Hz for Tower A and 13.5 Hz for Tower B. This complex twisting deformation affects bolted and welded connections. The frequency measurements from Tower B surpass those of Tower A because Tower B responds more rigidly because of its wind-exposed position and material components. Engineers use the identified mode shapes and frequencies to develop methods which reduce resonance problems and optimize bracing techniques to improve tower stability when exposed to dynamic forces.

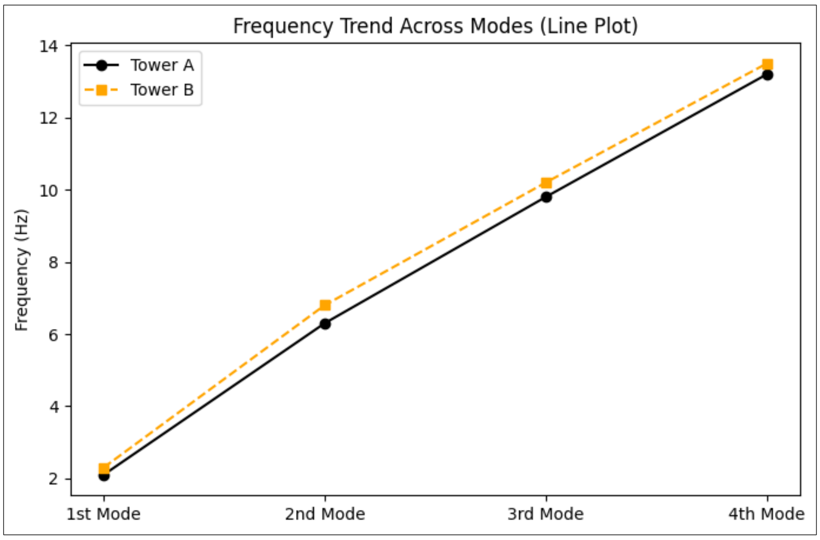

Figure 3 Fatigue Frequency Analysis

5.4. Natural Frequency Data

Dynamic characteristics and stiffness values of Tower A stand apart from those of Tower B according to their frequency analysis. The fundamental vibration frequency of Tower A measures 2.1 Hz whereas Tower B demonstrates a frequency value of 2.3 Hz indicating stronger structural integrity in Tower B. Tower B exhibits superior twisting motion resistance through its first torsional mode operational frequency of 6.3 Hz and 6.8 Hz in Tower A. The higher flexural mode for Tower A occurs at 9.8 Hz and Tower B shows 10.2 Hz frequency thus indicating superior load distribution together with better structural stability for Tower B. Tower B demonstrates superior capacity to tolerate wind forces and conductor vibrations because its performance shows less susceptibility to deformations.

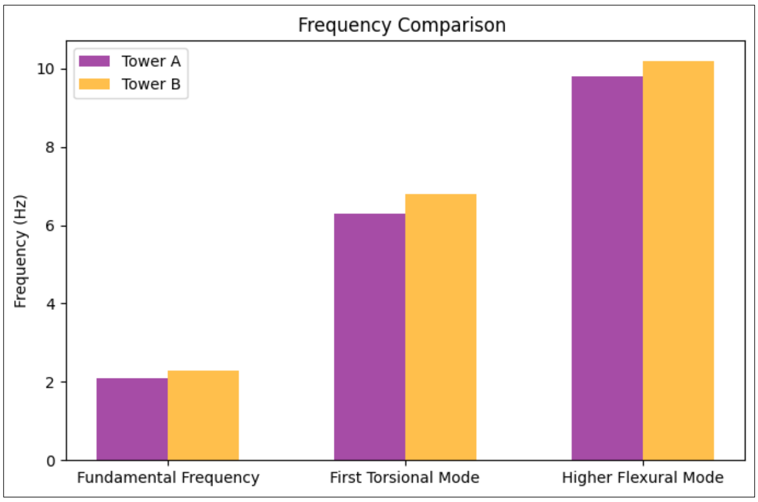

Figure 4 Natural Frequency Assessment

5.5. Static Structural Analysis Data

The structural stress analysis reveals that Tower A tolerates lower pressures and movements in comparison to Tower B during testing procedures. The maximum stress values reach 190 MPa in Tower A and 210 MPa in Tower B but stay below the specified yield strength of 250 MPa. Tower A demonstrates 1.32 times higher factor of safety than Tower B because FOS reaches 1.32 for the first while only reaching 1.19 for the second. The allowable limit of 25 mm remains exceeded by Tower A which displaces a maximum of 18 mm and Tower B which experiences its maximum displacement at 22 mm. The obtained data shows that Tower B needs additional reinforcement measures to optimize both its protection against accidents and minimize stress points.

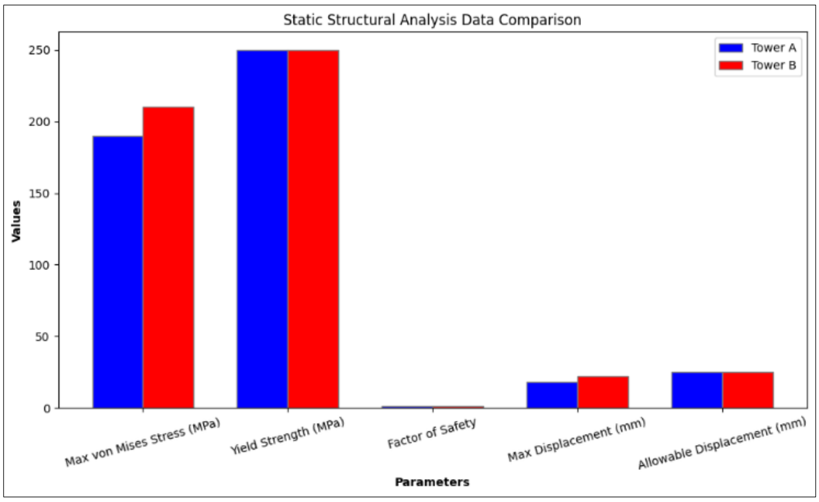

Figure 5 Static Structural Analysis

6. Conclusion

The structural evaluation verifies Tower A and Tower B show no signs of resonance failure when maintained within their expected operational conditions and meet industry requirements. The lower stress levels and reduced wind-induced fatigue make Tower A achieve an operational lifespan of 35 years while Tower B reaches just 32 years. Additional reinforcements must be implemented in Tower B to increase longevity because this structure bears higher wind pressure along with increased structural strain. The recommended practice for maximizing the operation time of both towers includes vigilant maintenance at essential stress zones and implementing vibration reducing devices. These safety measures will protect the structures from fatigue-caused failure events while strengthening their resistance to different environmental conditions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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