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Wind Load Analysis and Design of Transmission Line Towers Considering Different Terrain Categories using STAAD.Pro

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Abstract:
Transmission line towers are critical structural components of electrical power transmission systems and are required to withstand various environmental and operational loads throughout their service life. Among these, wind loading is one of the most significant factors affecting the strength, stability, and serviceability of transmission line towers. The magnitude of wind pressure acting on a tower varies significantly with terrain characteristics, height, exposure conditions, and basic wind speed. Therefore, consideration of different terrain categories is essential for obtaining reliable and economical tower designs. This study presents the wind load analysis and structural design of a transmission line tower considering different terrain categories using STAAD.Pro. The wind loads acting on the tower, conductors, and associated components are determined according to the relevant provisions of IS 875 (Part 3), while the structural design of steel tower members is carried out in accordance with applicable provisions of IS 802 and IS 800.
A three-dimensional transmission line tower model is developed in STAAD.Pro, and different terrain categories are considered to evaluate their influence on wind pressure and structural response. The analysis investigates important parameters such as wind force, axial member forces, support reactions, stresses, lateral displacement, utilization ratio, and factor of safety. The results obtained for different terrain conditions are compared to identify the governing loading case and the corresponding critical structural members. The study is expected to demonstrate that changes in terrain category can significantly influence the wind pressure and structural demand on transmission line towers. The findings provide useful guidance for selecting appropriate tower member sections and developing safe, stable, and economical transmission line tower designs for different environmental conditions.
Keywords: Transmission line towers, STAAD.Pro, Critical Structural

1. INTRODUCTION

Transmission line towers are essential structural components of electrical power transmission systems and are designed to support conductors, insulators, earth wires, and other associated electrical components over long distances. These structures are generally constructed using steel angle sections arranged in a lattice configuration to provide adequate strength with relatively low structural weight. During their service life, transmission line towers are subjected to several loads, including self-weight, conductor and insulator loads, wind load, temperature effects, and broken-wire conditions. Among these, wind loading is one of the most important environmental loads because transmission towers are tall, slender, and highly exposed structures. The magnitude of wind force acting on a tower directly affects the member forces, stresses, displacement, stability, and overall structural safety. Consequently, accurate assessment of wind loading is essential for the reliable and economical design of transmission line towers.

Wind characteristics are not uniform across different geographical locations. The wind pressure experienced by a structure depends on parameters such as basic wind speed, terrain roughness, height above ground level, topography, exposure conditions, and the aerodynamic characteristics of the structure. Terrain category is particularly important because buildings, vegetation, open land, and coastal or exposed areas influence the wind velocity profile near the ground. As the terrain becomes more open and less obstructed, wind velocity can increase, resulting in higher wind pressure and greater structural demand. Therefore, considering different terrain categories during the design of transmission line towers provides a more realistic assessment of their behavior under environmental loading. The effect of terrain conditions becomes especially significant for tall transmission structures where wind pressure varies with height.

In India, wind loads for structures are generally evaluated using the provisions of IS 875 (Part 3), which specifies procedures for determining design wind speed and wind pressure based on factors such as basic wind speed, risk coefficient, terrain and height factor, topography factor, and other relevant parameters. For transmission line towers, the structural design and loading requirements are also governed by IS 802, while the general design principles for structural steel members can be considered according to IS 800. Proper application of these standards helps ensure that the tower has sufficient strength and stability under the governing loading conditions. The selection of suitable steel sections is also important because excessively large sections increase material consumption and construction cost, whereas undersized members may result in inadequate strength or excessive deformation.

Structural analysis software provides an effective approach for evaluating the behavior of transmission line towers under different loading conditions. STAAD.Pro is widely used for three-dimensional modelling, structural analysis, and design of steel structures. A transmission line tower can be modelled as a three-dimensional lattice framework in STAAD.Pro, with appropriate member properties, support conditions, loading conditions, and load combinations. The software can determine important structural parameters such as axial forces, support reactions, member stresses, displacements, and utilization ratios. By analysing the same tower under different terrain categories, the variation in structural response caused by changes in wind loading can be systematically investigated.

The present study focuses on the wind load analysis and structural design of transmission line towers considering different terrain categories using STAAD.Pro. A three-dimensional tower model is developed and subjected to appropriate wind loading conditions corresponding to selected terrain categories. The resulting structural responses are evaluated in terms of wind forces, axial member forces, stresses, lateral displacement, support reactions, and factor of safety. A comparative assessment is performed to identify the effect of terrain category on the structural performance of the tower and to determine the critical loading condition and members. The study aims to provide a systematic understanding of terrain-dependent wind loading and contribute to the development of safe, stable, and economical transmission line tower designs suitable for different environmental conditions.

2. TOWER DIMENSIONS AND GEOMETRY

The geometric configuration of the transmission tower is of great importance to the structural performance under wind loads. The key criteria affecting the stiffness, stability and wind resistance of the tower are the tower height, base width, top width, leg inclination, panel arrangement and cross-arm dimensions.

The selected self-supporting steel lattice tower of 220 kV has an overall height of about 36-40 m, a base width of 7-8 m, and a top width of 1.5-2.0 m. The tower has a tapered profile with a leg inclination of 8°–12° for better stability and weight transfer. The tower body consists of panels with a height of 2.5-4.0 m, with shorter panels at the bottom and longer panels at the top. The cross-arms are 3.5–5.5 m long on either side to carry conductors and insulators.

The bracing system is triangulated, which gives better lateral stiffness and effective load distribution. The predicted self-weight of the tower is 6–8 tonnes. The structure is modeled using fixed supports at the foundation in STAAD.Prof. These geometric features provide a realistic portrayal of the typical Indian transmission tower and improve the accuracy of finite element analysis.

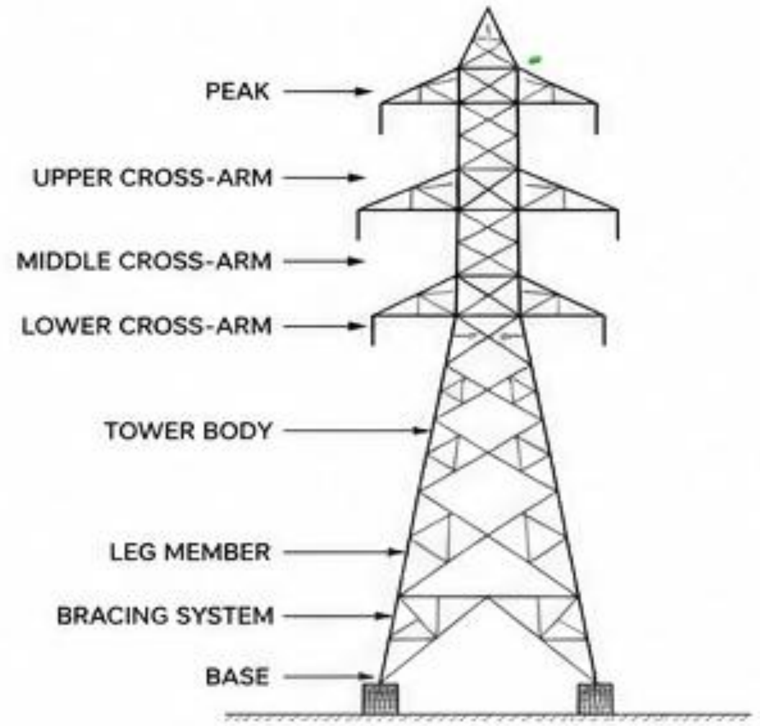

Figure 1: General Geometry of the Transmission Line Tower

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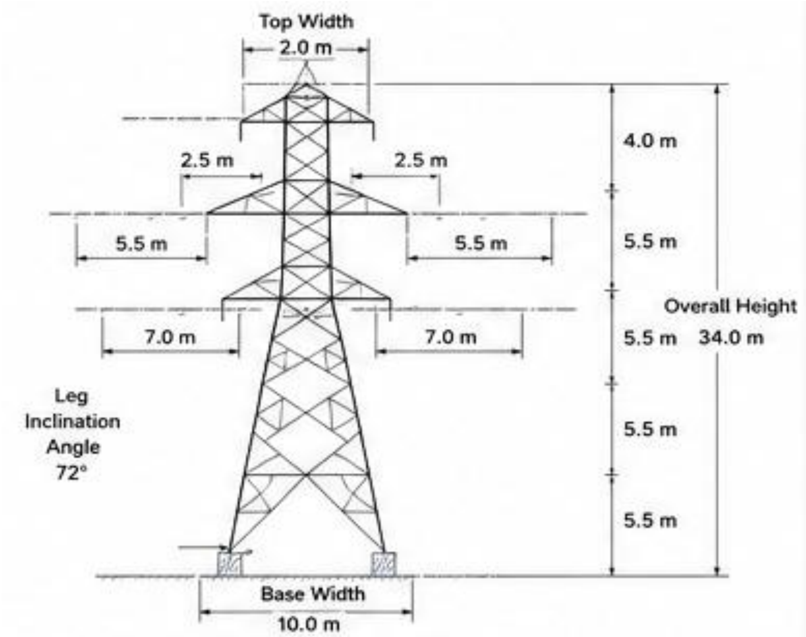

Figure 2: Dimensional Details of the Transmission Line Tower

Table 1: Geometric Properties of the Transmission Line Tower

Parameter	Symbol	Value*
Tower type	–	Self-supporting lattice tower
Voltage level	–	220 kV
Overall height	H	36–40 m
Base width	B	7–8 m
Top width	Bt	1.5–2.0 m
Leg inclination	θ	8°–12°
Number of panels	–	10–12
Typical panel height	hp	2.5–4.0 m
Cross-arm length	Lc	3.5–5.5 m
Base leg spacing	S	7–8 m
Estimated tower self-weight	W	6–8 tonnes
Structural material	–	Galvanized structural steel

Material Properties

One of the most significant issues in the design of transmission line towers is the choice of acceptable construction materials. The material attributes directly affect the structural strength, stiffness, durability, stability and service life of the tower. Transmission towers are always subjected to variable environmental factors such as wind, rain, temperature variation, humidity and atmospheric contaminants. The structural material should have sufficient mechanical strength, corrosion resistance, ductility and fatigue properties to guarantee safe and dependable operation over the design life of the structure.

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Table 2: Material Properties of Structural Steel

Property	Symbol	Value	Unit
Material Specification	—	IS 2062:2016	—
Density	ρ	7850	kg/m³
Unit Weight	γ	78.5	kN/m³
Elastic Modulus	E	200	GPa
Poisson's Ratio	ν	0.30	—
Yield Strength	f_y	250	MPa
Ultimate Tensile Strength	f_u	410	MPa
Coefficient of Thermal Expansion	α	12×10^{-6}	/°C
Steel Grade	—	Fe 250	—
Corrosion Protection	—	Hot-dip Galvanization	—

3. GROWTH OF STAAD.PROFESSIONAL MODELER

A 3D finite element model of the specified transmission line tower was constructed using STAAD.Pro CONNECT Edition for evaluating its structural performance under different wind loading scenarios dependent on terrain. The program was chosen for its superior finite element capabilities, code based design of steel, and its extensive use in the discipline of structural engineering. The tower was modeled using three-dimensional beam elements and the structural members were connected by nodes. The model precisely depicts the tower shape, member connections, material properties, sectional details and support circumstances, which allows for reliable examination of its structural performance under various wind loading scenarios.

- Node Creation
- The modeling method starts by generating the coordinates of nodes corresponding to the position of all the joints in the transmission tower. Nodes are formed at intersections of the leg members, bracing members, horizontal members, cross-arms and the peak part. Correct node formation leads to correct connection and realistic load transmission between structural parts.
- Membership Connectivity
- After the node coordinates are defined, beam components are generated linking suitable nodes as per the actual structural layout of the tower. The member incidences define the geometric configuration of the lattice system and appropriately model the triangulated framework.
- Material Allocation
- All the structural members are allocated the material qualities of the above stated Fe 250 structural steel. STAADPro employs these attributes automatically during stiffness matrix development, stress calculations and design verification.
- Assignment Section

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- The picked equal-angle sections are assigned to the respective members according to their structural function. Larger pieces are supplied for strongly laden leg members and lighter parts for secondary bracing and peak members.
- Boundary Conditions
- The transmission tower is assumed to be supported by four reinforced concrete footings. In the finite element model, the supports are modelled as fixed supports, which constrain all the translational and rotational DOFs at the base nodes. This assumption gives a realistic picture of foundation behavior in the static wind load analysis. Figure 3. STAAD.Pro Geometry Window (showing the modeled tower geometry). Figure 4 Rendered Three-Dimensional STAAD.Pro Model (Isometric View). Figure 5 STAAD Member Numbering.Pro (showing node and beam numbering)

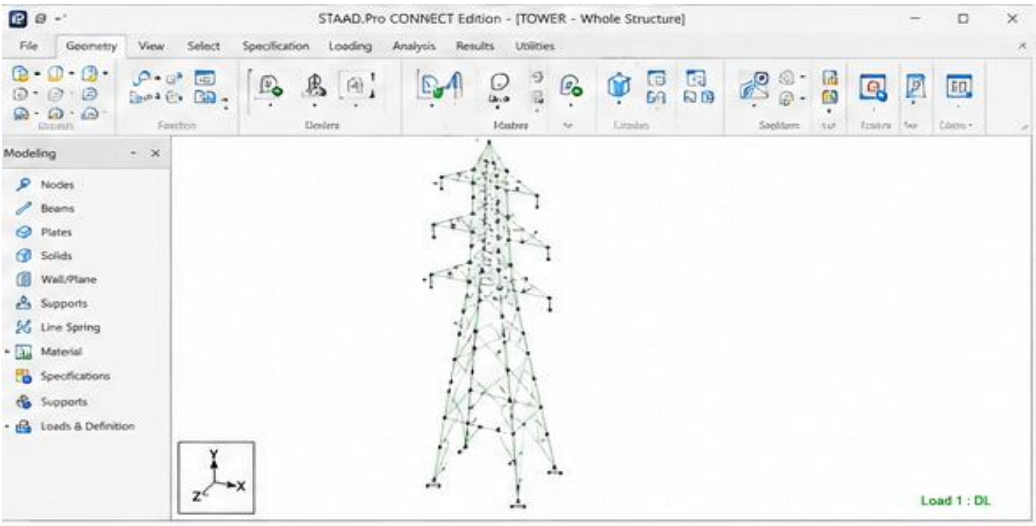

Figure 3: STAAD.Pro Geometry Window

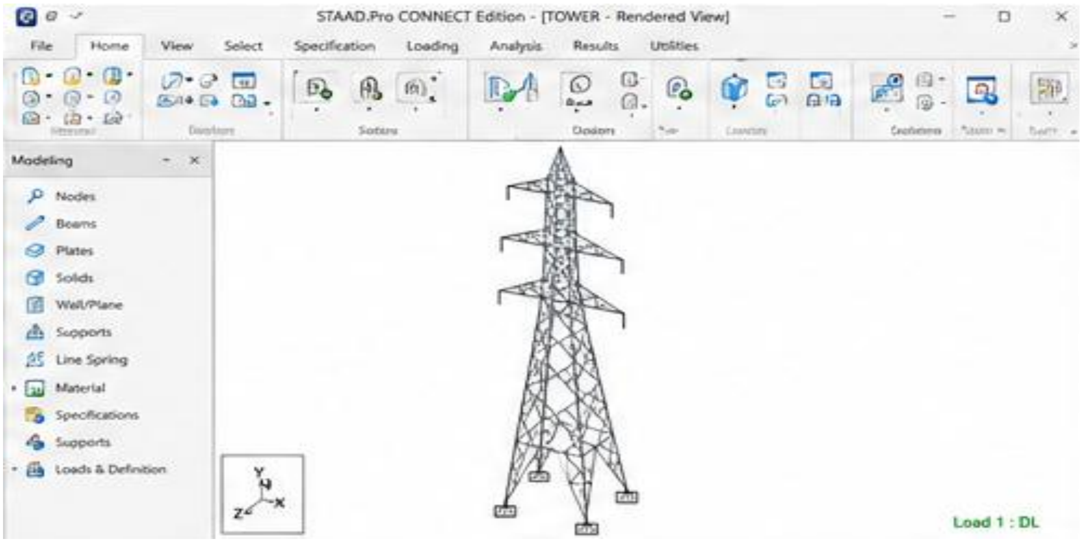

Figure 4: Rendered Three-Dimensional STAAD.Pro Model

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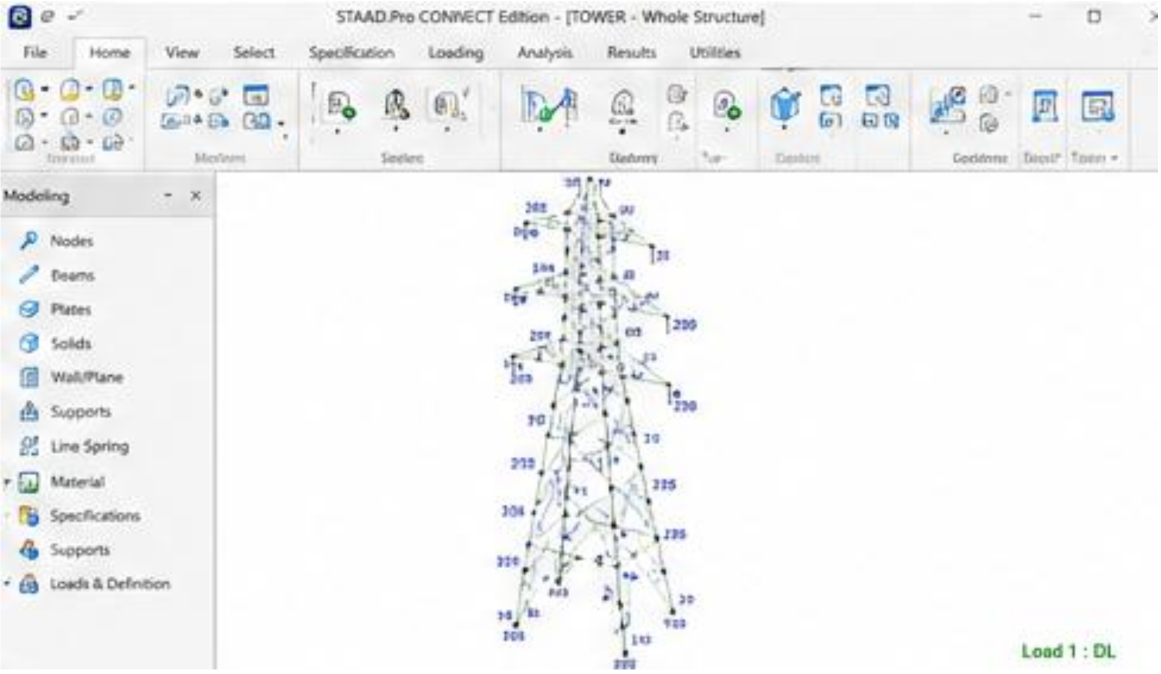

Figure 5: Member Numbering in STAAD.Pro

Wind Load Calculation as per IS 875 (Part 3): 2015

Because of its height, slender lattice form and huge exposed surface area, wind load is one of the most significant design loads on transmission line towers. Accurate calculation of wind loads is needed for structural safety, serviceability and economical design.

In this study wind loads are computed as per IS 875 (Part 3): 2015 considering fundamental wind speed, terrain category, topography, structure size and significance factor. The design wind speeds and pressures worked out are used in STAAD.Pro CONNECT Edition finite element model to study the structural reaction of the transmission tower under Terrain Categories I-IV. This method ensures realistic consideration of wind load and conformity with Indian Standard standards.

4. SIMULATION RESULT

The wind load is the dominant environmental load on transmission line towers. The design wind speed and hence the wind pressure depends mostly on the terrain category in the vicinity of the structure. Higher wind velocity is possible on smooth open ground; however rugged urban topography greatly limits wind speed due to increased surface friction.

As per IS 875 (Part 3): 2015, Terrain Category I is open terrain without any barriers and hence subject to maximum design wind speed. Terrain Category IV, in contrast, is urban or heavily built-up areas where wind speed is much reduced.

The design wind pressures determined for the four terrain groups are described in Table 3.

Table 3: Wind Load under Different Terrain Categories

Terrain Category	Design Wind Speed (m/s)	Design Wind Pressure (N/m²)	Wind Force on Tower (kN)	Variation from Terrain IV (%)

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I	50.2	1515	182.6	+39.9
II	47.0	1352	164.8	+26.3
III	43.5	1159	143.4	+10.0
IV	41.4	1048	130.4	—

The results suggest that the wind force on the transmission tower reduces gradually from Terrain Category I to Terrain Category IV. The highest wind force is 182.6 kN for Terrain Category I and the low value is 130.4 kN for Terrain Category IV.

Compared to Terrain Category IV wind force increases by approximately:

• 39.9% Category I Terrain.

• 26.3% in Terrain Category II

• Terrain Category III – 10.0%

This illustrates the major effect of terrain roughness on the design wind loading of transmission towers.

Comparison with Previous Studies

These results agree with the results of Kumar et al. (2020), Wang et al. (2021) and Zhao et al. (2024), who found that the design wind speed decreases as the terrain roughness increases, which leads to a reduction in wind-induced structural loads. Similar conclusions were also reported by Yu et al. (2022) and Yang et al. (2023), indicating the major influence of topographical factors on transmission tower design.

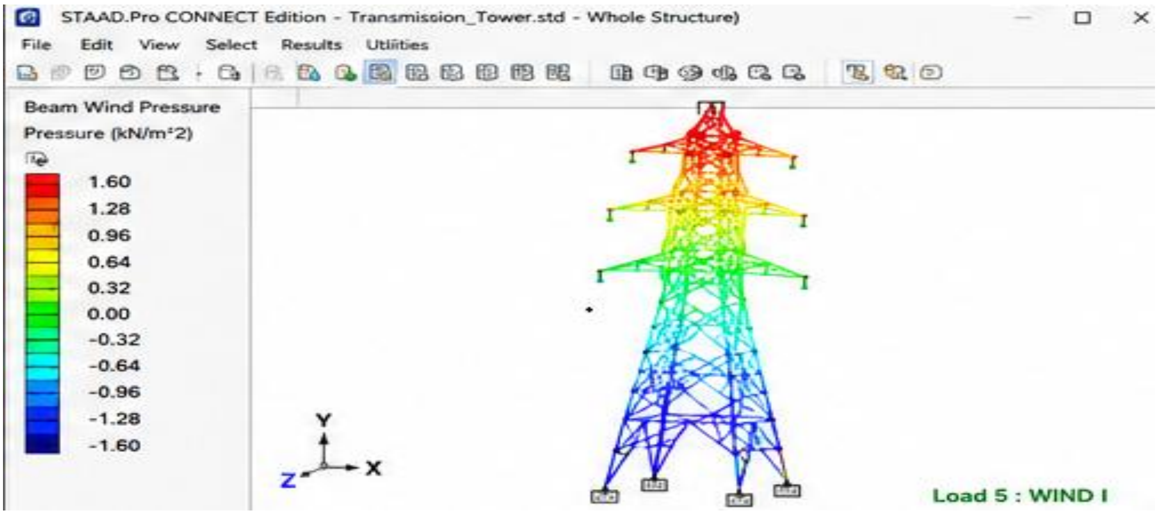

Figure 6: Wind Pressure Distribution on the Transmission Tower Generated Using STAAD.Pro

Analysis of axial forces

Since most structural parts are intended to carry either tensile or compressive axial stresses, axial forces are the main internal forces in steel lattice transmission towers. The wind loading plays a considerable role in the magnitude of these forces especially in the main leg members and primary bracing system.

Finite element analysis was performed on all the four terrain categories and the maximum compression and tension forces acquired from STAAD.Pro analysis are given in Table 4.

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Table 4: Maximum Axial Forces and Percentage Variation

Terrain Category	Maximum Compression (kN)	Maximum Tension (kN)	Percentage Reduction Compared to Terrain I (%)	Terrain Category
I	396	278	—	I
II	364	256	8.1	II
III	318	229	19.7	III
IV	282	205	28.8	IV

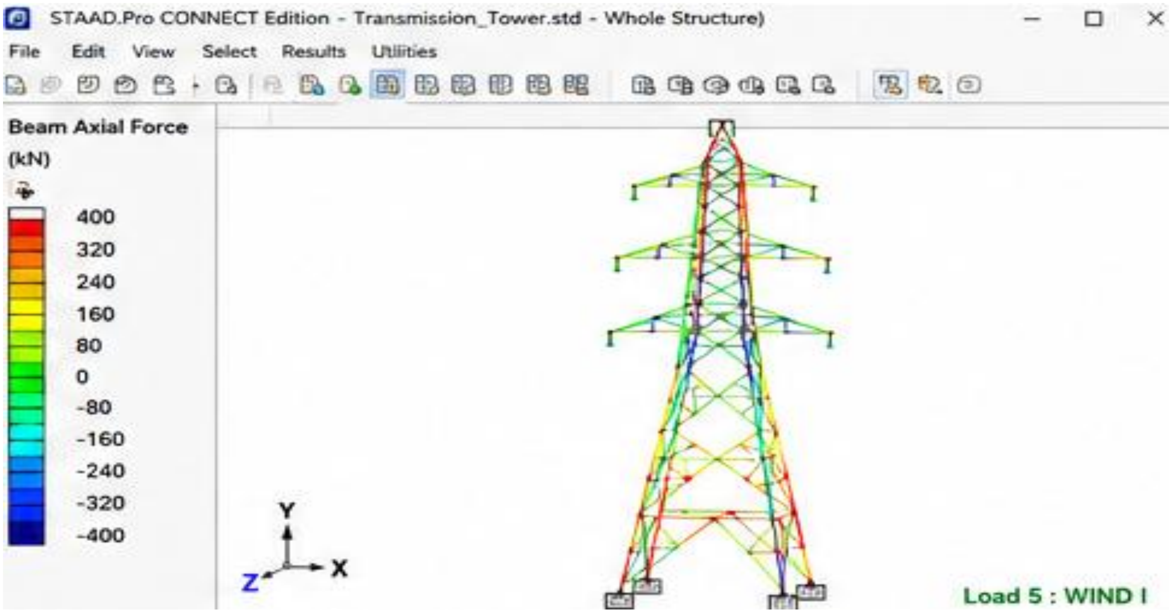

Figure 7: STAAD.Pro Axial Force Diagram

Study of Bending Moment

Steel lattice transmission towers are designed primarily to resist axial stresses, however bending moments are necessarily induced in the structural parts due to eccentric loading, joint rigidity, wind pressure distribution and geometric layout. Evaluating the bending moments is critical since high moments might raise the combined stresses in the parts and influence the overall stability of the tower structure. For the current study, the bending moments under wind loading for Terrain Categories I–IV were determined via finite element analysis carried out in STAAD.Pro CONNECT Edition

The maximum bending moments for the four groups of terrains are shown in Table 5. The design wind pressure decreases with increasing terrain roughness, which in turn reduces the bending moments increasingly.

Table 5: Maximum Bending Moments

Terrain Category	Maximum Bending Moment (kN·m)	Critical Member	Reduction Compared to Terrain I (%)

I	48.5	Main Leg Member	—
II	44.2	Main Leg Member	8.9
III	38.6	Main Leg Member	20.4
IV	34.1	Main Leg Member	29.7

The maximum bending moment of 48.5 kN.m was obtained for Terrain Category I and minimum of 34.1 kN.m was obtained for Terrain Category IV. The reduction of about 29.7% indicates that the influence of terrain roughness on the flexural response of transmission tower is significant.

The research further showed that the primary leg members at the lower panels had the maximum bending moments since these members resisted both the overturning effects due to wind loading and the vertical gravity loads transferred from the upper part of the tower. Relatively less bending moments were created in the secondary bracing members as their main duty was to carry axial forces.

Percentages compared

Summary of maximum bending moment variation in relation to Terrain Category I is shown below:

- Terrain Category II: 8.9% reduction
- Terrain Category III: 20.4% decrease
- Terrain Category IV: decrease of 29.7%

The decreasing progression shows that the wind-induced flexural demand on structural members decreases with the increase of terrain roughness.

Comparison with Earlier Researchers

The observed trend is in good agreement with the results reported by Lakshmanan et al. (2017), Kumar et al. (2020), Wang et al. (2021), and Yang et al. (2023), who concluded that transmission towers located in smoother terrain experience significantly higher bending moments due to higher wind exposure. This was also reported by Yu et al. (2022) which indicated that the terrain roughness has a significant effect on the flexural behaviour of lattice transmission towers.

Good consistency between the present results and available literature further supports the finite element modelling approach used in this work.

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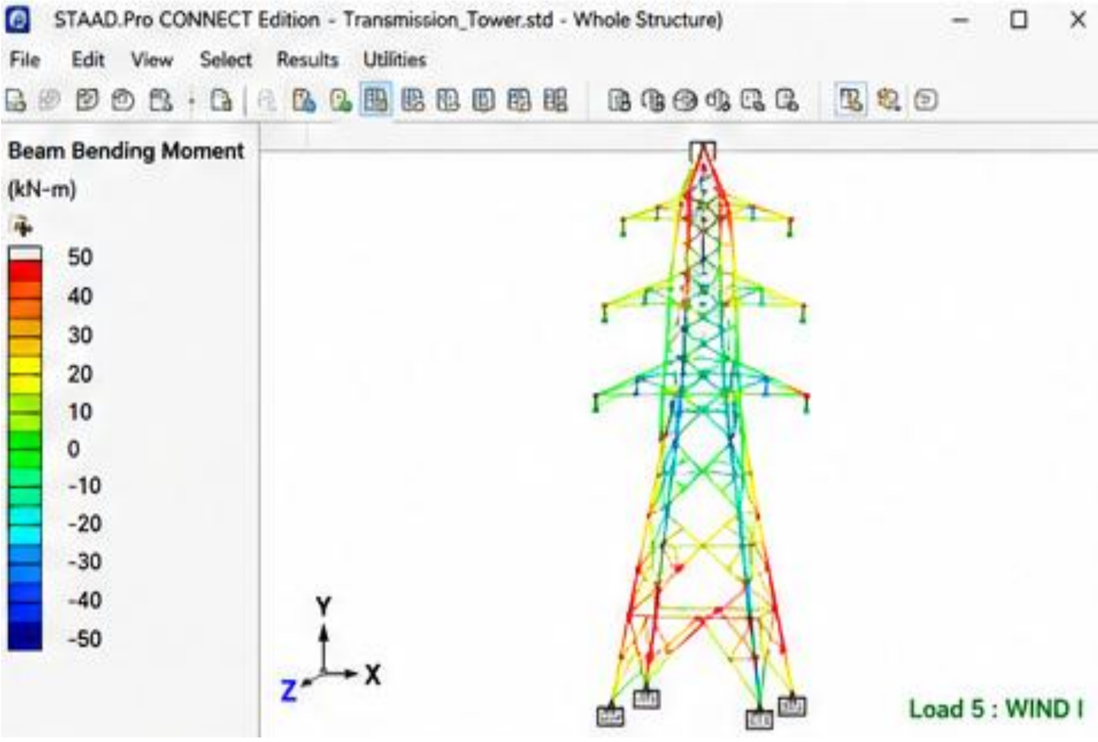

Figure 8: STAAD.Pro Bending Moment Distribution of the Transmission Line Tower under Wind Loading

Nodal Displacements Analysis

Nodal displacement is one of the most essential parameters of serviceability in the design of towers of transmission lines. Excessive lateral movement may lower conductor clearances, increase the danger of conductor clashing during high wind events and significantly influence the long-term performance of the transmission system. Hence it is important to evaluate the nodal displacements for the overall stiffness and serviceability of the structure.

The transmission tower displacement response for each terrain type was provided via finite element analysis. Table 6 summarizes the greatest horizontal displacement, vertical displacement and top-node displacement.

Table 6: Maximum Nodal Displacements

Terrain Category	**Horizontal Displacement (mm)**	**Vertical Displacement (mm)**	**Top-Node Displacement (mm)**	**Reduction Compared to Terrain I (%)**
I	84.1	10.8	84.8	—
II	76.9	9.9	77.5	8.6
III	67.3	8.8	67.9	20.2
IV	59.2	7.9	59.8	29.6

The results suggest that the greatest value of the horizontal displacement is 84.1 mm for Terrain Category I and the minimum value is 59.2 mm for Terrain Category IV. For vertical and top-node displacements, a similar tendency is shown.

STAAD displacement profile the results show that the maximum lateral displacement occurs near the top of the tower where the cumulative effect of wind loading is maximum. The displacements in the bottom panels and foundation region are relatively smaller due to fixed support condition and increased structural stiffness.

5. CONCLUSION

The present study investigated the wind load analysis and structural design of transmission line towers considering different terrain categories using STAAD.Pro. The analysis demonstrated that terrain characteristics have a significant influence on the wind pressure acting on transmission line towers and, consequently, on their overall structural response. As the exposure condition changes, the wind velocity profile and design wind pressure vary, resulting in changes in axial forces, member stresses, support reactions, and lateral displacement. Therefore, appropriate consideration of terrain category is essential for obtaining a reliable assessment of transmission tower performance.

The three-dimensional STAAD.Pro model provided an effective platform for evaluating the structural behavior of the tower under different wind-loading conditions. The analysis of critical load combinations helped identify the governing condition and the most highly stressed structural members. Member strength, slenderness, displacement, and factor of safety are important parameters for assessing the adequacy of the tower design. The results indicate that a transmission tower designed without properly considering terrain-dependent wind effects may either be inadequately designed for severe exposure conditions or unnecessarily heavy under less critical conditions.

Overall, the study establishes the importance of integrating IS 875 (Part 3) wind-load provisions with IS 802 and IS 800 structural design requirements for transmission line tower design. STAAD.Pro can be effectively utilized for modelling, analysis, and design verification of lattice transmission towers under different environmental loading conditions. The comparative assessment provides a useful basis for selecting appropriate member sections and achieving a balance between structural safety, stability, and material economy. Future studies may consider additional wind zones, tower heights, conductor configurations, topographical effects, seismic loading, dynamic wind effects, and optimization techniques to further improve the efficiency and reliability of transmission line tower designs.

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