Finite element analysis of wind-induced response in tapered steel floodlight poles with varied luminaire configurations

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Abstract. Stadium floodlight poles are tall, slender structures that are especially sensitive to wind loads, which often shape their design and construction. This study uses finite element analysis in STAAD. Pro to examine a 30-meter tapered steel floodlight pole. Wind loads are calculated as per IS 875 (Part 3): 2015. The analysis primarily focuses on a comparative study of four regular luminaire headframe configurations with flexibility and structural performance in mind. The result of the numerical calculations indicated that the adjustable brackets could increase the lateral deflection of the structure by as much as 7.7%. Due to the introduction of brackets, the peak stress value increased by 34% due to stress concentration. This was compared against the baseline case of the most critical wind zone having a wind speed of 61 m/s. The base pole can deflect as much as 530.795 mm due to wind loads. This is 12.5 times higher than the IS 800 serviceability limit of 100 mm. Thus, performance penalties of actual headframe designs must be measured. Also, such structures must be checked for serviceability early on since meeting strength requirements does not guarantee safety and usability of wind-sensitive structures.

1 Introduction

Tall, thin structures like telecom towers, wind turbines, and high-mast lighting poles are examples of modern architecture. These structures are extremely sensitive to wind and other dynamic forces because of their shape, low mass, and damping. Large movements, obvious deflections, and high stresses from wind loads can jeopardize the safety of any structure. History is full of cautions. Similar to 1940, aerodynamic forces caused the Tacoma Narrows Bridge to collapse. These forces are still not completely understood.

1.1 Background and problem statement

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High-mast floodlight poles are important for sports stadiums as they enable events to occur at night. Usually, these poles are designed with tapered steel standards. However, the fixtures installed at the top may differ. Some feature fixed arms, while others are equipped with adjustable brackets which allow for precise aiming. Some come complete with extra masts to enhance height. Each design alters the way the pole responds to wind and its weight distribution. There hasn't yet been much published research on how these typical headframe differences affect overall structural performance. This gap is important for engineers who must weigh structural safety against the demand for adjustable lighting. Lack of data can inadvertently create stress concentrations or excessive flexibility in designs. The objective of the study is to measure the structural impacts of these recurrent lumenaire configurations.

1.2 Research objectives and scope

This study's primary objective is to fill the data gap by methodically contrasting the structural performance of various designs. There are three distinct goals for the study:

1. Create comprehensive finite element models of four typical luminaire headframe designs for a 30-meter tapered steel floodlight pole.

2. Use IS 875 (Part 3): 2015 to analyze wind loads and observe how the pole reacts in various wind zones.

3. Examine each design's structural performance, paying particular attention to maximum bending stress (structural strength) and maximum lateral deflection (usability).

This study focuses on static analysis using standard wind pressure codes, which is how these structures are typically designed. This study establishes the foundation for further research on more intricate dynamic and fatigue behaviors, even though dynamic effects like vortex shedding and resonance are not discussed here.

Two major contributions are made in this paper. First, it gives engineers clear information about the structural trade-offs of various luminaire headframe designs. Second, it demonstrates that under wind loads, a typical preliminary design might not satisfy important usability requirements. This result emphasizes the necessity of careful usability testing and robust early design when engineering wind-sensitive structures.

2 Literature review

The literature review looks at important statistical ideas in wind engineering, which are the basis for codes like IS 875 [10]. This sets the stage. It talks about how new ways of computing, like the Finite Element Method (FEM), are being used to study monopole structures. The review also talks about older studies that looked at how attachments and changes in geometry can make stress concentrations worse. This study compares the standard method used here with more thorough full-scale monitoring. This puts it in the context of what is currently being done. The primary deficiency identified is the absence of targeted, quantitative research contrasting the structural effects of prevalent luminaire headframe variations, a deficiency this paper seeks to rectify, as illustrated in Table 1.

Table 1. Summary of literature review and identified research gap.

Literature	Major Point of Study	Takeaways & Limitations
Mengistu et al. (2023) [1]	Full-Scale Monitoring	Provides real-world data for validating design models, highlighting the limitations of the purely codified approach adopted in this study.
Fousi & Chaithra (2017) [2]	Stress Concentration from Appurtenances	Demonstrated that adding geometric features increases local stress, which directly supports this study's key finding regarding adjustable brackets.
Lonare et al. (2020) [3]	Comparative Material Analysis (Steel vs. FRP)	Compared steel and FRP poles under wind loading. Provides material comparison context, though the present study focuses on steel pole optimization with brackets.
Vinay & Arunakanthi (2023) [4]	Stadium Infrastructure Design & 3D Modelling	Applied design principles to large-scale stadium infrastructure. Demonstrates practical application of structural analysis in sports facility.
Cui & Wang (2023) [7]	Nonlinear Wind Effects on Wind-Sensitive Structures	Comprehensive review of nonlinear wind effects on flexible structures. Establishes theoretical context for wind sensitivity, though present study uses linear-elastic FEA.
Ramkumar & Ramakrishnan (2022) [8]	Advanced Computational Modelling (CFD-FEA)	Used coupled CFD-FEA to study complex effects; this positions the current paper's FEA-only approach as a focused, standard-of-practice analysis.
Zhang et al. (2021) [9]	Wind-Induced Vibration Countermeasures	Identified countermeasures for wind-induced vibrations in tall structures. Provides practical mitigation strategies.

3 Analytical methodology

This part gives a thorough, organized, and repeatable description of the analytical process used in this study. The methodology is based on the Finite Element Method (FEM) and follows the rules set by Indian Standards for designing structures and wind loads. Figure 1 shows the steps that were taken.

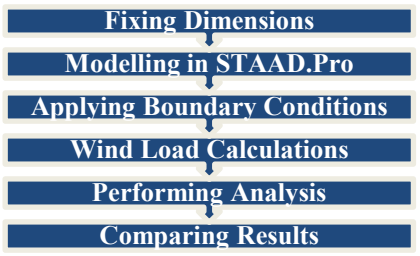

Fig. 1. Methodology.

3.1 Structural model and configurations

The structural analysis was centred on a three-dimensional finite element model of a tapered, hollow, circular steel floodlight pole. All modelling and analysis were performed using the commercial software package STAAD Pro, a widely used tool in structural engineering.

3.1.1 Baseline pole geometry and material properties

The baseline monopole was modelled as a 30-meter-high cantilevered structure. It features a linear taper, with a base diameter of 700 mm and a top diameter of 556 mm. The pole is constructed from structural steel with a uniform wall thickness of 12 mm throughout its height. The material properties assigned to the model conform to the standards for structural steel as specified in IS 800: 2007. The key geometric and material properties are summarised in Table 2.

Table 2. Geometric and material properties of the floodlight pole model.

Parameter	Value	Unit
Total Height (H)	30	m
Base Diameter (D_{base})	700	mm
Top Diameter (D_{top})	556	mm
Wall Thickness (t)	12	mm
Material	Structural Steel	-
Young's Modulus (E)	2.0×105	N/mm²
Poisson's Ratio (ν)	0.3	-
Density of Steel (ρ)	7850	kg/m³

3.1.2 Boundary conditions

To simulate its real-world installation, the base of the pole (Node 1 at an elevation of 0.0 m) was modelled with a fully fixed support. This boundary condition restrains all six degrees of freedom (three translational and three rotational), representing a rigid connection to a substantial concrete foundation and ensuring that all loads are transferred into the ground without rotation or displacement at the base.

3.1.3 Luminaire configurations

The core of this study is a comparative analysis of four distinct luminaire headframe configurations. Each configuration was modelled by adding beam elements to the top of the baseline pole model, representing the structural members of the luminaire assembly.

1. **Configuration 1: Straight arm.** This is the baseline model, representing the simplest design. It consists of a simple, straight cantilevered arm assembly extending from the

top of the pole to hold the light fixtures, as displayed in Figure 2.

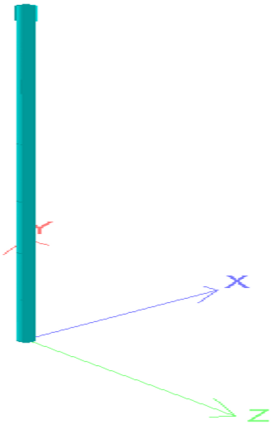

Fig. 2. A 3D rendering view of "Straight Arm" configuration.

2. **Configuration 2: Straight arm with adjustable brackets.** This model builds upon the first by introducing adjustable brackets. In the FE model, the mechanical joints of these brackets are represented by connections with released moments, simulating their pinned nature This introduces points with lower rotational stiffness. This is an important factor in the following analysis of deflection and stress, as shown in Figure 3.

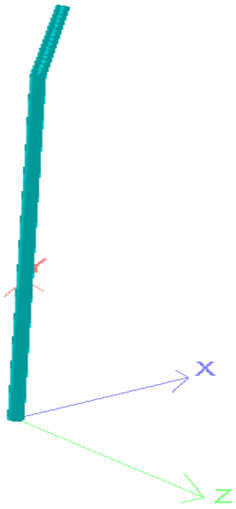

Fig. 3. A 3D rendering view of the "Straight Arm with adjustable brackets" setup.

3. **Configuration 3: Straight arm with masts.** This configuration includes extra vertical structural members, or masts, that rise from the straight arm. This design raises the overall height of the luminaires, which increases the moment arm for the wind loads acting on them, as shown in Figure 4.

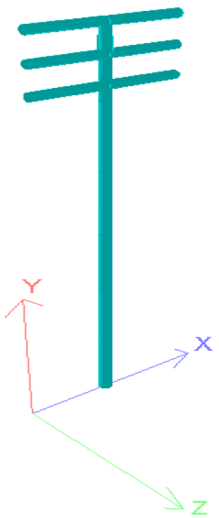

Fig. 4. A 3D rendering view of the "Straight Arm with Masts" configuration.

Configuration 4: Straight Arm with Adjustable Brackets and Masts. This is the most complex model. It combines the features of the second and third designs. It includes both the vertical masts and the mechanically jointed adjustable brackets. This configuration provides maximum operational versatility but also has the most significant structural complexity, as shown in Figure 5.

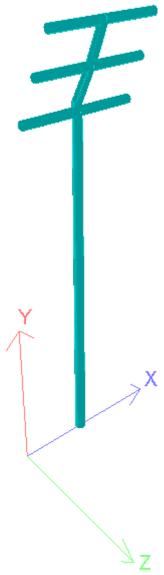

Fig. 5. A 3D rendering view of the "Straight Arm with Adjustable Brackets and Masts" setup.

3.2 Wind load formulation per IS 875:2015 (Part 3)

The wind loads on the structure were calculated according to the Indian Standard IS 875 (Part 3): 2015, which provides a framework for determining wind forces on buildings and structures.

3.2.1 Governing equations

The design wind speed at any height z above ground level, V_z, is calculated using the following formula:

$$V_z = V_b \cdot K_1 \cdot K_2 \cdot K_3 \quad (1)$$

Where:

- Vb is the basic wind speed for the geographical location.
- K1 is the probability factor or risk coefficient. It considers the design life of the structure and the acceptable level of risk.
- K2 is the terrain roughness, height, and structure size factor. It considers how wind speed changes with height and the characteristics of the surrounding terrain.
- K3 is the topography factor. It accounts for the local effects of isolated hills, ridges, or cliffs.

After the design wind speed Vz is calculated, the design wind pressure Pz is calculated using the formula:

$$P_z = 0.6(V_z)^2 \quad (2)$$

Where P_z is in N/m² and V_z is in m/s. In order to find the wind force, the calculated pressure is applied.

3.2.2 Selection of parameters and zone analysis

The study looked at the pole's performance in four hypothetical wind zones, each with different wind speeds and terrain features. Each zone represented a unique mix of basic wind speed and terrain features. The value for the topography factor, K3, was set to 1.0 for all zones, assuming the structure is located on flat, uniform terrain with no significant topographical features. The values for K1 ranged from 1.06 to 1.08, which are typical for important structures with a design life of 100 years. The terrain category determines the K2 factor and reflects the ground roughness; Category 2 represents open terrain with well-scattered obstructions, Category 3 represents terrain with numerous closely spaced obstructions, and Category 4 represents terrain with immense and innumerable obstructions (e.g., large city centres). The parameters for each zone, along with the resulting design wind pressures at the top of the 30-meter pole, are summarised in Table 3.

Table 3. Wind load parameters and calculated pressures per IS 875[10].

Parameter	Zone-I	Zone-II	Zone-III	Zone-IV
Basic Wind Speed (V_b)	50.0 m/s	44.0 m/s	50.0 m/s	39.0 m/s
Terrain Category	1	1	1	1
Risk Coefficient (K1)	1.08	1.07	1.08	1.00
Height Factor (K2) at 30m	1.150	1.150	1.150	1.150
Topography Factor (K3)	1.0	1.0	1.0	1.0
Wind Speed (Vz)	62.1 m/s	54.14 m/s	62.1 m/s	44.85 m/s
Design Wind Pressure (Pz)	2.3 kN/m²	1.75 kN/m²	2.3 kN/m²	1.2 kN/m²

3.3 Finite element analysis (FEA) implementation

The FEA was executed as a linear static analysis using STAAD. Pro. The tapered pole and headframe components were modelled using 3D beam elements. These elements are justified as they are suitable for modelling slender members where bending, shear, and axial deformations are the primary [10] [11] modes of response. The pole's tapered geometry was modelled directly using the software's tapered section feature, which discretizes the member along its length. As such, a manual mesh refinement criterion for area or solid elements did not apply to this modelling approach. The calculated design wind pressure [12] was used as a distributed load along the pole's height, as illustrated in the load application schematic (Figure 6).

3.3.1 Load application

Three primary load cases were defined in the model:

1. **Dead Load (DL):** The self-weight of the steel pole and headframe assembly was automatically calculated by STAAD. Pro based on the defined geometry and material density. It was applied as a body force in the negative global Y-direction.
2. **Live Load (LL):** The weight of the luminaires and associated equipment was modelled as a series of concentrated nodal loads applied at the attachment points on the headframe assembly, also acting in the negative global Y-direction.
3. **Wind Load (WL):** The calculated design wind pressure (Pz) was applied as a uniformly distributed load along the projected area of the pole's height. The intensity of this load was varied with height in accordance with the profile defined by the K2 factor in IS 875[10]. Wind loads were applied separately in the global X and Z directions to simulate wind from different angles, as displayed in Figure 6.

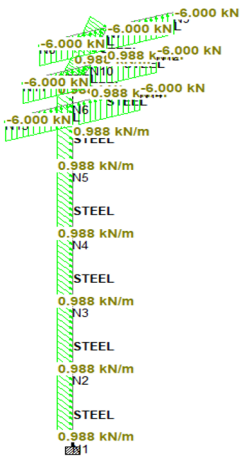

Fig. 6. Finite element model of the pole under applied wind pressure distribution along its height.

3.3.2 Load combinations

To determine the maximum (worst-case) structural response, the primary load cases were combined using load factors as stipulated in Table 4 of IS 800: 2007 for the limit state design of steel structures. Key combinations included, but were not limited to:

- 1.5 (DL + LL)
- 1.2 (DL + LL + WL)
- 1.5 (DL + WL)

The analysis was run for all relevant load combinations, and the results presented in the following section represent the envelope of the maximum deflections and stresses obtained from this comprehensive set of scenarios.

4 Results and discussion

The finite element analysis produced detailed data on how the four floodlight pole designs performed under wind loads. This section reviews and discusses the results, focusing on lateral deflection (serviceability) and bending stress (structural strength). The discussion explains the key mechanical behaviors and their impact on design.

4.1 Influence of luminaire configuration on lateral deflection (serviceability analysis)

The lateral deflection at the top of the pole is an important sign of the structural serviceability of high-mast systems. Too much deflection can cause luminaire misalignment, discomfort for the public, and possible fatigue at connections. Table 4 shows the maximum lateral deflections measured for each luminaire configuration in the four wind zones.

Table 4. Comparative analysis of maximum lateral deflection (mm).

Configuration	Zone-I (mm)	Zone-II (mm)	Zone-III (mm)	Zone-IV (mm)
Straight Arm	524.037	396.997	524.037	306.255
Straight Arm With Brackets	530.795	402.299	530.795	310.568
Straight Arm With Masts	502.329	334.343	502.329	294.502
Straight Arm With Brackets & Masts	423.681	445.662	423.681	333.947

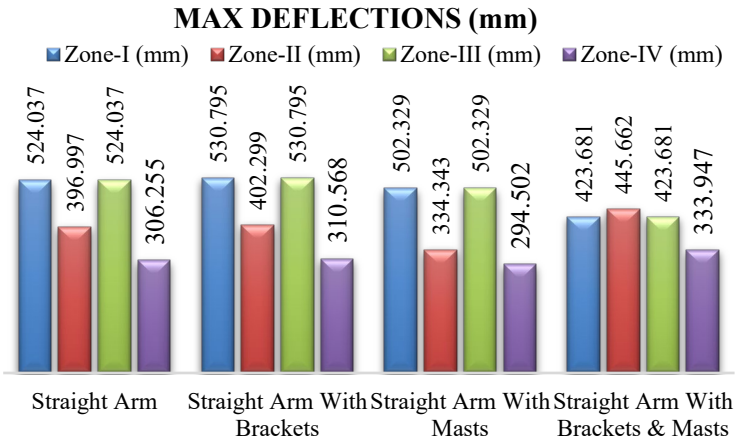

Fig. 7. Maximum deflection of poles in various zones.

The data clearly show that both wind zone intensity and luminaire arrangement have a big impact on lateral deflection. As expected, Zone-III, with the highest wind speed, causes the largest deflections in all designsThe maximum deflection is 530.795 mm for the Straight Arm with Brackets (Configuration 2), which is only 1.3% greater than the baseline Straight Arm (524.037 mm). Configuration 3, which uses only masts, shows a slight increase in stiffness while reducing deflection by 4.1% when compared to the baseline. Configuration 4, which includes both brackets and masts, has the lowest deflection at 423.681 mm, which is 19% less than the baseline. This indicates that the additional supporting members in the combined design enhance lateral stiffness and aid in bending resistance.

All designs exceed the permitted deflection when considering the serviceability limit from IS 800 (H/300 = 100 mm for a 30,000 mm pole). The deflection of even the best model (Configuration 4 in Zone-III) is four times the limit at 423.681 mm.This shows that the current pole design, no matter the headframe, does not provide enough stiffness, as shown in Figure 7.

In real use, such large deflections would cause visible movement, misaligned lights, and possible fatigue cracks in welded joints. These results highlight the need to optimize the pole's size and material thickness early in the design to ensure good serviceability under strong winds, as shown in Figure 8.

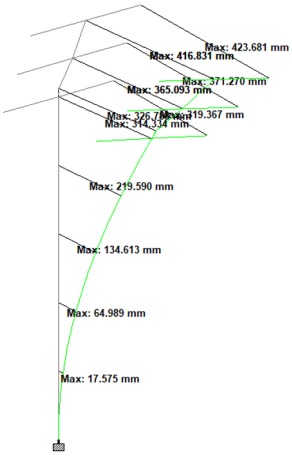

Fig. 8. Highest lateral deflection of the pole in wind zone iii for 4th configuration.

4.2 Bending and concentration stresses analysis using ultimate limit state analysis

Deflection is important for serviceability, but bending stress determines the ultimate limit state, how well the structure can handle maximum loads without failing. The highest bending stresses usually happen at the pole's fixed base, as summarized in Table 5.

Table 5. Comparative analysis of maximum bending stress (N/mm²).

Configuration	Zone-I (N/mm²)	Zone-II (N/mm²)	Zone-III (N/mm²)	Zone-IV (N/mm²)
1: Straight Arm	87.77	67.23	98.76	51.88
2: Straight Arm w/ Brackets	87.69	67.54	132.42	52.12
3: Straight Arm w/ Masts	229.35	67.23	98.76	51.88
4: Straight Arm w/ Brackets & Masts	200.99	68.32	100.36	52.72

While all designs remain within the typical steel strength limits, they exhibit localized stress concentrations that may eventually lead to fatigue. To lessen these effects, some flexibility and good connection details are crucial. For instance, Configuration 2's Zone III stress is 34% higher than the baseline, indicating a concentration of stress at the bracket connections.

Despite lower wind pressure in Zone I, Configuration 3 has the highest stress (229.35 N/mm²), indicating a localized stress build-up at the mast connections. When compared to Configuration 3, the combined design (Configuration 4) reduces peak stress, demonstrating the useful flexibility that adjustable brackets can provide. Also, the critical wind zone shifts

from Zone III in standard poles to Zone I in mast-based designs, highlighting the complex relationship between geometry and wind loads. Figure 9 depicts a graph of maximum pole bending stresses in different zones.

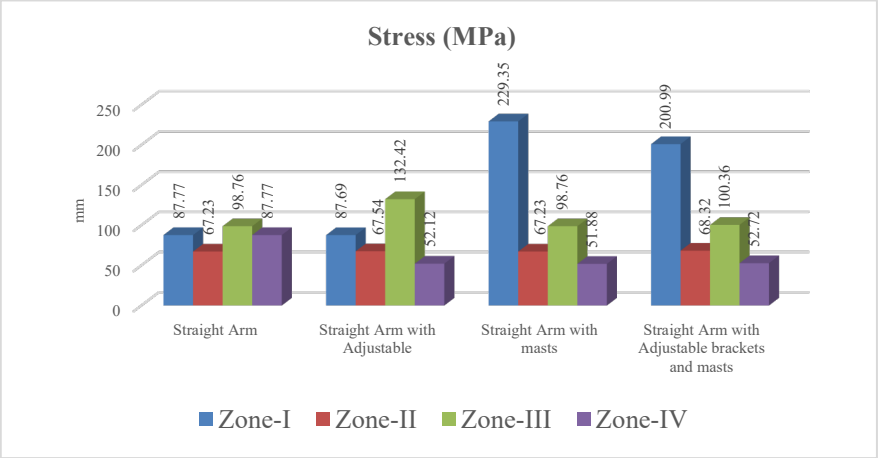

Fig. 9. Maximum pole bending stresses in different zones.

Significant structural behaviors are revealed by the bending stress analysis. When Configurations 1 and 2 are compared in Zone III, maximum stress increases dramatically from 98.76 N/mm² to 132.42 N/mm²—a 34% increase—while deflection increases only slightly (about 1.3%). This demonstrates how stress concentrations result from bracket connections. Stress flow is disrupted by abrupt changes in geometry and bolted joints, creating localized high-stress areas that may result in fatigue. Despite lower wind pressure in Zone I, Configuration 3 (Straight Arm with Masts) has the highest stress (229.35 N/mm²), probably because of sharp corners or stiff welds at the mast connection. The lower stress of 200.99 N/mm² in the combined design (Configuration 4) indicates that adjustable brackets provide flexibility and aid in stress distribution. This calls into question the notion that stiffer, welded structures are always superior and emphasizes the significance of precise connection details and some degree of flexibility. Zone III is the critical wind zone for maximum stress for standard poles (1 and 2), but Zone I, where wind speed increases more with height, is the critical wind zone for high-mast designs (3 and 4). This shows that taller, more complex structures need specific analysis, not just general rules, as shown in Figure 10.

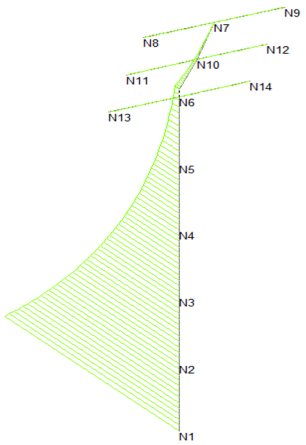

Fig. 10. Stress contour plot of highest bending stress area.

5 Conclusions

This finite element study evaluated how a high-mast floodlight pole performs under wind loads with different luminaire setups. The main conclusions are:

1. The most critical wind condition for lateral deflection is in Zone-III. All the configurations exceed the IS 800 serviceability limit of H/300 = 100 mm.
2. The usage of adjustable brackets possesses some advantages, which are gained at the cost of creating stress concentration zones, hence increasing local stresses up to 34%.
3. Adding masts increases the overall bending stresses. For taller setups, the critical load case shifts to Zone I due to the steeper wind speed profile with height.
4. The base pole design is not strong enough. All the configurations produce lateral deflections well above the permissible limit, showing a need for more stiffness and a redesign in geometry or materials.
5. Findings from the current work emphasized the importance of early considerations of serviceability and stress concentration evaluations in the design stages; this helps ensure deflection control and fatigue resistance.
6. This study highlights the need to consider serviceability and stress concentrations early in the design process. Doing so helps control deflection and improve fatigue resistance before the fabrication.

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