Wind Load Analysis of Curved Roof Structures: Influence of Foundation Soil and Terrain Conditions

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***Abstract*—Curved roof structures are widely used for their aesthetic appeal and structural efficiency but are highly susceptible to wind-induced forces. This study numerically analyzes wind load effects on curved roof structures, focusing on medium soil conditions and wind speeds across Delhi, Ahmedabad, Bengaluru, and Port Blair. Using STAAD Pro, key parameters such as base shear, overturning moment, and maximum displacement were evaluated under varying wind scenarios. Findings reveal a direct correlation between wind intensity and structural demand, with higher wind speeds leading to increased base shear, overturning moments, and displacements. Despite these effects, all structural responses remained within permissible limits, ensuring operational safety. Design recommendations emphasize reinforcements and optimized stiffness in high-wind regions to enhance performance. This study highlights the importance of site-specific wind load considerations in curved roof structure design, providing insights for safer, more resilient architectural solutions.**

***Index Terms*—Wind Load, Curved Roof, STAAD Pro, Structural Response, Base Shear, Overturning Moment, Displacement.**

I. INTRODUCTION

Wind is the movement of air due to atmospheric pressure differences, creating turbulent boundary layer flows influenced by surface roughness and obstacles. Low-rise structures, common in civil engineering, experience significant wind effects, particularly on their roofs, which vary in shape—flat, pitched, gable, hipped, or curved.

Curved roofs are widely used in structures requiring large, unobstructed spans, such as exhibition halls, sports arenas, and airport hangars. Constructed with lightweight materials, they are highly susceptible to wind-induced suction pressures due to turbulence within the atmospheric boundary layer. Their aerodynamic behavior depends on factors such as rise-to-span ratio, wind incidence angles, turbulence intensity, and Reynolds number. As the rise-to-span ratio increases, wind flow separation shifts leeward, altering pressure distribution. This study analyzes wind load effects on curved roofs, considering key aerodynamic parameters to enhance their structural stability and efficiency.

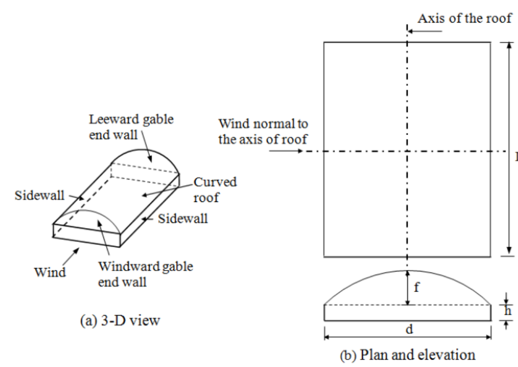

Figure 1 Schematic diagram of a curved roof at elevated level

Research on wind loads and structural responses of curved roof structures has evolved significantly over the past three decades. Studies can be broadly categorized into experimental investigations using wind tunnel tests and analytical studies utilizing Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) simulations.

Kwon et al. (2016) developed a web-based aerodynamic database for wind analysis of low-rise buildings. Sharma et al. (2023) numerically analyzed wind pressure distribution on different roof shapes using Ansys CFX and found that cylindrical and dome roofs experience lower suction pressures due to reduced flow separation. Singh & Roy (2019) explored roof slope effects on pyramidal roofs, revealing that optimized slopes can enhance wind resistance. Zhou et al. (2019) and Rani & Ahuja (2017) focused on dome and circular canopy roofs, emphasizing the importance of wind tunnel testing and CFD simulations in understanding wind behavior.

Sakib et al. (2021) reviewed wind loads on canopies, highlighting their susceptibility to wind-induced pressures, while Sun et al. (2014) investigated Reynolds number effects on semi-cylindrical roofs, demonstrating variations in drag coefficients with increased turbulence. Ding et al. (2014) studied aerodynamic stiffness and damping, concluding that unsteady aerodynamic forces significantly influence dynamic responses.

Verma & Ahuja (2015) examined wind pressure on domical and cylindrical roofs, demonstrating that aerodynamic performance is highly dependent on wind incidence angles. Abraham et al. (2013) investigated side walls' impact on wind loads, showing that structural elements like parapets alter pressure distributions. Yang et al. (2013) introduced a novel Proper Orthogonal Decomposition (POD) method for estimating wind-induced responses, offering improved precision over conventional approaches.

Several studies, including Castelli et al. (2011) and Zhou et al. (2012), explored wind load response on large-span roofs, proposing modified methodologies for equivalent static wind load predictions. Melbourne (1995) and Holmes & Paterson (1993) used aero-elastic models and turbulence simulations to assess wind load variations based on rise-to-span and length-to-span ratios.

These studies underscore the critical role of roof geometry, wind turbulence, and terrain conditions in determining wind-induced pressures on curved roofs. The insights gained provide a framework for optimizing curved roof design, ensuring structural stability and resilience against wind loads.

Table 1 Previous Literature

Author(s)	Methods Used	Key Findings	Limitations
Aram Alizadegan et al. (2024)	Computational Fluid Dynamics (CFD) simulation	Increased concavity of tall curved buildings increases suction and overturning moments	Structural efficiency decreases beyond certain curvature levels
Ji Yao et al. (2024)	Numerical simulations of variable cross-section roofs	Suction pressure at roof middle increases with rise-to-span ratio below 0.3; further increases reduce suction	Lack of extensive real-world validation
Aditya Kumar Jha et al. (2022)	CFD simulation of pitched and circular roofs	Sharp-edged pitched roofs generate higher wind forces compared to smooth circular roofs	Limited to specific configurations; lacks general applicability
Edmundo Amaya-Gallardo et al. (2021)	Reynolds-Averaged Navier Stokes (RANS) simulation	Mean pressure coefficients highly sensitive to roof curvature and wind direction	Limited validation data for vaulted canopy roofs
K. Bala Venkata Sai et al. (2021)	STAAD Pro software simulation for wind loads on multistory curved buildings	Wind load significantly affects bending moments and shear forces; structure stiffness varies with wind direction	Does not account for dynamic wind effects
Jian Guo et al. (2020)	Analytical approach for calculating wind load shape factor	Identified sensitivity of long-span stadium roofs to wind loads; current codes insufficient for complex curved surfaces	Absence of definitive methods for calculating wind load shape factor
Monalisa Mallick et al. (2019)	CFD and wind tunnel studies on C-shaped buildings	Roof curvature significantly reduces pressure coefficients compared to non-curved designs	Limited analysis on surrounding environmental factors

Author(s)	Methods Used	Key Findings	Limitations
Mikel Ogueta Gutierrez et al. (2016)	Wind tunnel tests on curved roof over a football stadium	Highlighted the complexity of wind load calculations on uniquely designed curved roofs; standard codes insufficient for such designs	Limited by the complexity of multi-segmented curved roof designs
Yuan-Lung Lo (2016)	Hermite polynomial translation for non-Gaussian pressure spectra	Roof curvature and Reynolds number significantly affect wind-induced pressure spectra	Limited to non-Gaussian pressure characteristics
Wei Ding et al. (2014)	Wind tunnel experiments and CFD simulations on vibrating curved roofs	Unsteady aerodynamic forces impact dynamic response; reduced frequency critical to roof behavior	Limited parameter range in wind tunnel experiments

This study aims to analyze the wind load effects on curved roof structures by evaluating the impact of foundation soil conditions, terrain categories, and wind incidence angles using STAAD Pro. It investigates structural response parameters, including base shear, overturning moment, and displacement, while validating results against experimental and theoretical models. The findings will contribute to practical design guidelines for improving the safety and performance of curved roof structures under varying wind conditions.

The research follows a systematic approach, beginning with a comprehensive literature review to establish the framework for analyzing wind-induced pressures on curved roofs. A parametric analysis is conducted to assess the influence of geometric factors, including rise-to-span ratio, wall height, and roof curvature, on wind pressure distribution. Wind load simulations in STAAD Pro incorporate varying wind incidence angles and turbulence intensities, considering open, suburban, and urban terrain conditions to capture surface roughness effects. Additionally, soil-structure interaction is modeled using medium soil conditions to study its influence on load transfer mechanisms. The numerical simulations focus on key structural parameters such as displacement, stress concentration, and load distribution, with validation performed by comparing results with available experimental data and theoretical models. A detailed load combination assessment is carried out to identify potential vulnerabilities in structural performance. Finally, design recommendations are proposed to enhance the stability and resilience of curved roof structures under diverse wind conditions.

Table 2 Material Properties of Structural Elements and Soil Conditions

Material Type	Grade/Type	Elastic Modulus (E) (GPa)	Poisson's Ratio (ν)	Density (kN/m³)
Concrete	M30	30	0.2	25
Steel Reinforcement	Fe500	200	0.3	78.5
Soil	-	25	0.35	-

Table 3 Sectional parameters

Structural Component	Cross-Section (mm)	Dimensions (m)	Remarks
Vertical Columns	450 × 450	15	Fixed supports
Horizontal Beams	300 × 300	16	Main structural beams
Inverse Beams	300 × 300	16	Provides additional support
Curved Roof Slab	200 mm thick	16.0 × 8.0	Arched profile for wind load analysis
Total Structure Width	-	16	Full width of the structure

Total Structure Height	-	23	Includes 15m column height + 8m roof height
Additional Floor Level Height	-	3	Intermediate level consideration

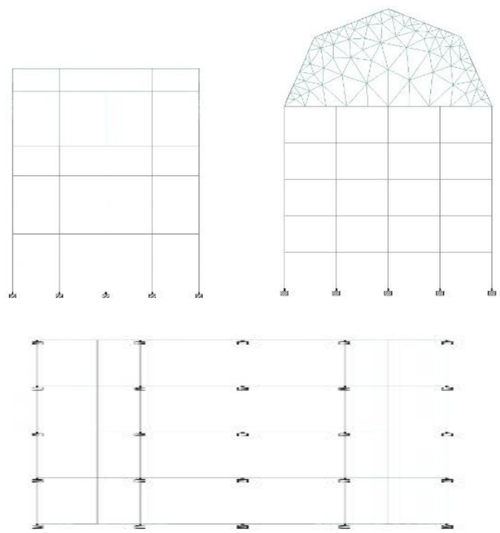

Figure 2 (a) Front View, (b) Side View, and (c) Top View of curved roof building

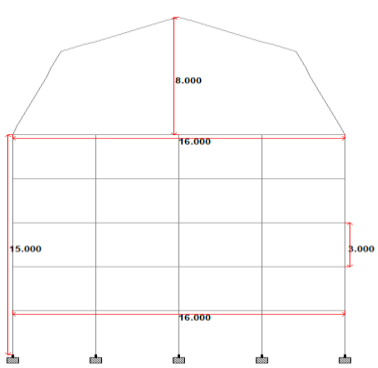

Figure 3 Detailing of the Curved roof building

Table 4 Wind load Parameter

City	Basic Wind Speed	Terrain Considerations
Delhi	50 m/sec	Urban terrain, high exposure
Ahmedabad	39 m/sec	Semi-arid terrain, moderate wind exposure
Bengaluru	33 m/sec	Urban/suburban terrain, low to moderate exposure
Port Blair	44 m/sec	Coastal terrain, very high exposure

1. Output of analysis

The wind analysis of the curved roof grid frame structure using STAAD Pro evaluates structural behavior under wind load conditions for Delhi and Ahmedabad, with a medium soil foundation. The study examines base shear, displacement, and overturning moments, revealing the impact of wind speed variations on structural stability. Findings highlight the relationship between wind forces and structural response, aiding in optimized design decisions to enhance safety, stability, and efficiency under realistic environmental conditions.

Table 5 Maximum outcomes for each condition

Condition	Wind Zone	Wind speed	Base Shear (kN)	Maximum Resultant Displacement (mm)	Overturning Moment (kN-m)
Run 1	Delhi	50 m/s	1665.42	8.949	51.37
Run 2	Ahmadabad	39 m/s	1595.389	5.684	48.83
Run 3	Bengaluru	33 m/s	1520.325	4.356	47.707
Run 4	Port Blair	44 m/s	1616.294	7.06	49.91

II. RESULTS AND DISCUSSION

2.1. Overturning Moment

The overturning moment at the base of the curved roof grid frame structure is crucial for rotational stability under wind loads. Analysis shows that Delhi (51.37 kN-m at 50 m/s) experiences the highest overturning moment, followed by Port Blair, Ahmedabad, and Bengaluru with decreasing wind speeds. Displacement and base shear values follow a similar trend, with higher wind speeds leading to greater structural deformation. These findings highlight the impact of wind intensity on stability, emphasizing the need for robust design strategies in high-wind regions.

2.2. Base Shear

The base shear, representing horizontal forces on the foundation, varies with wind speed across locations. Delhi (1665.42 kN at 50 m/s) experiences the highest base shear, followed by Port Blair, Ahmedabad, and Bengaluru with decreasing values. This trend highlights the impact of wind intensity on lateral forces, emphasizing the need for robust foundation designs to ensure structural stability in high-wind regions.

2.3. Maximum Displacement

The displacement analysis highlights the maximum resultant displacement at critical nodes, emphasizing structural stability under wind loads. Delhi (8.949 mm at 50 m/s) records the highest displacement, followed by Port Blair, Ahmedabad, and Bengaluru with decreasing values. The results confirm that higher wind speeds lead to greater structural deformations, underscoring the need for optimized flexibility and stiffness in design. These findings emphasize location-specific considerations to ensure structural resilience and performance in high-wind regions.

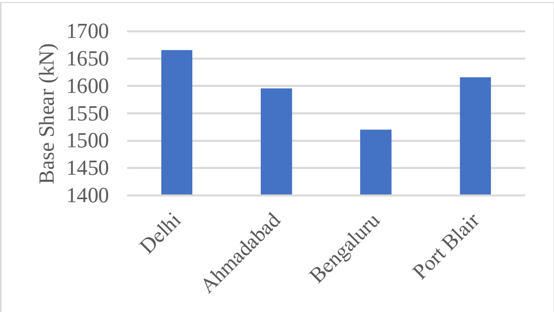

Figure 4 Base shear comparison for different condition

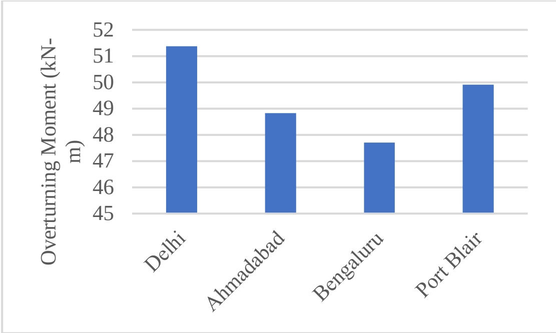

Figure 5 Overturning moment comparison for different condition

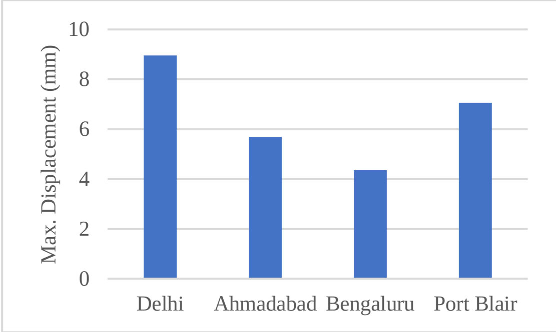

Figure 6 Top Displacement comparison for different condition

III. CONCLUSION

This study analyzed the structural performance of a curved roof grid frame structure under varying wind conditions across Delhi, Ahmedabad, Bengaluru, and Port Blair using STAAD Pro. The results highlight the significant impact of wind speed variations on key structural parameters, including base shear, overturning moment, and displacement.

Key findings indicate that higher wind speeds (e.g., Delhi, Port Blair) lead to increased base shear and overturning moments, necessitating robust structural and foundation designs. Displacements remained within permissible limits, though they increased with wind intensity, emphasizing the need for reinforcements in high-wind zones. The study confirms that wind loads dominate structural response over foundation properties, reinforcing the importance of location-specific design considerations.

By incorporating wind load analysis into structural design, this research provides valuable guidelines for optimizing stability, resilience, and durability of curved roof structures in diverse environmental conditions.

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