

HEIGHT-DEPENDENT WIND RESPONSE CHARACTERIZATION OF REINFORCED CONCRETE VERTICAL BUILDING SYSTEMS

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Abstract - The increasing demand for vertical construction in urban environments has intensified the significance of wind effects in the design of reinforced concrete (RC) building systems. As building height increases, structural response becomes highly sensitive to lateral wind loads, necessitating a detailed understanding of height-dependent behavior. This study investigates the wind-induced response characteristics of a G+16 RC building using five different structural configurations developed through three-dimensional finite element modeling in SAP2000. Wind loads are applied in accordance with IS 875 (Part 3):2015 using the equivalent static method. Key response parameters, including lateral displacement, storey drift, base shear, and fundamental time period, are evaluated and compared across models. The results indicate that lateral displacement increases nonlinearly with height, with maximum values occurring at the top storey, while peak storey drift is observed in the mid-to-upper levels. The incorporation of shear walls significantly enhances structural stiffness, reducing displacement and drift by approximately 35–55% compared to the bare frame system. Dual and optimized structural configurations demonstrate superior performance, offering improved stability and serviceability under wind loading. Additionally, an inverse relationship between structural stiffness and fundamental time period is observed. The findings provide valuable insights into the selection of efficient structural systems for mid-rise RC buildings and contribute to improved wind-resistant design practices.

Key Words: Wind load, Reinforced concrete, Height-dependent response, Lateral displacement, Storey drift, Shear wall systems, SAP2000, Structural optimization

1. INTRODUCTION

1.1 Background

1.1.1 Urbanization and Growth of Vertical Infrastructure

Rapid urbanization has significantly transformed the built environment, particularly in developing countries where population growth and limited land availability necessitate vertical expansion. The increasing demand for residential, commercial, and institutional spaces has led to the widespread adoption of mid- and high-rise reinforced concrete (RC) buildings. This vertical growth not only optimizes land use but also improves infrastructure

efficiency and urban functionality. Advancements in construction materials, structural systems, and analytical tools have further enabled engineers to design taller and more complex buildings with enhanced safety and performance. However, as building height increases, the influence of lateral loads becomes more critical, shifting design focus from gravity-dominated behavior to lateral load resistance (Taranath, 2016).

1.1.2 Increasing Dominance of Wind Loads in Mid/High-Rise Buildings

With increasing building height, wind loads emerge as a governing factor in structural design, particularly in regions with moderate seismic activity. Unlike gravity loads, wind loads vary with height and time, producing complex pressure distributions and dynamic effects on structures. Mid-rise buildings, such as G+16 configurations, fall within a transitional range where wind effects begin to significantly influence structural response. These effects include lateral displacement, inter-storey drift, and dynamic amplification due to turbulence and vortex shedding. Standard design provisions, such as IS 875 (Part 3):2015, provide a framework for estimating wind loads; however, they may not fully capture the complexity of wind-structure interaction in taller buildings (Holmes, 2015).

1.1.3 Importance of Structural System Selection

The selection of an appropriate structural system plays a crucial role in determining the performance of buildings under wind loading. Different systems, such as moment-resisting frames, shear wall systems, and dual systems, offer varying levels of stiffness and load-resisting capacity. Flexible systems tend to experience higher displacement and drift, while stiffer systems provide better control over lateral deformation. Therefore, the choice and configuration of structural elements directly influence both safety and serviceability. Efficient structural system selection is essential not only for controlling wind-induced responses but also for achieving economical and optimized designs (Smith and Coull, 1991).

1.2 Wind-Induced Structural Behavior

1.2.1 Along-Wind, Across-Wind, and Torsional Effects

Wind-induced structural behavior is complex and can be categorized into along-wind, across-wind, and torsional responses. Along-wind effects occur in the direction of the mean wind flow and are primarily associated with static pressure acting on the building surface. Across-wind effects arise due to vortex shedding, which generates oscillatory forces perpendicular to the wind direction, often leading to significant dynamic response in slender structures. Torsional effects occur when there is an **অসম্ম**metrical distribution of mass or stiffness, causing rotational motion about the vertical axis. These combined effects make wind analysis a multidimensional problem requiring detailed evaluation of structural response under varying conditions (Simiu and Scanlan, 2003).

1.2.2 Serviceability Concerns: Displacement, Drift, and Acceleration

Wind-induced responses primarily affect the serviceability performance of buildings rather than ultimate strength. Lateral displacement is a key indicator of overall structural flexibility and tends to increase with height. Storey drift, defined as the relative displacement between consecutive floors, is critical in preventing damage to structural and non-structural components. Excessive drift can lead to cracking, façade damage, and functional issues within the building. Additionally, wind-induced acceleration affects occupant comfort, particularly in upper storeys, where perceptible motion can cause discomfort or anxiety. Therefore, controlling displacement, drift, and acceleration within permissible limits is essential for ensuring both structural safety and user comfort (Kwok et al., 2009).

1.3 Research Gap

1.3.1 Limited Studies on Mid-Rise (G+16) Height-Dependent Response

Although extensive research has been conducted on low-rise and very tall buildings, relatively fewer studies focus on mid-rise structures where wind effects begin to dominate but are often underestimated. Buildings in the G+16 range represent a transitional category where both static and dynamic wind effects are significant. The lack of detailed investigation into height-dependent response behavior in such structures creates uncertainty in design practices and highlights the need for focused research in this area.

1.3.2 Lack of Comparative Evaluation of RC Systems under Identical Wind Loads

Existing literature often examines individual structural systems in isolation, without providing a consistent comparative framework. There is a notable lack of studies

that evaluate multiple RC structural configurations—such as moment-resisting frames, shear wall systems, and dual systems—under identical geometric and loading conditions. This limits the ability to clearly understand the relative efficiency of each system in resisting wind loads and controlling structural response.

1.3.3 Over-Reliance on Simplified Codal Methods

Design practices frequently rely on simplified codal approaches, such as the equivalent static method prescribed in IS 875 (Part 3):2015. While these methods are practical for routine design, they often neglect important dynamic effects such as gust response, higher mode participation, and wind-structure interaction. This over-reliance can lead to either conservative or unconservative designs, particularly in mid- to high-rise buildings. Consequently, there is a need for detailed numerical analysis and performance-based evaluation to achieve more accurate and reliable predictions of wind-induced behavior (Kareem and Kijewski, 2002).

2. LITERATURE REVIEW

2.1 Wind Engineering in Tall Buildings

2.1.1 Overview of Wind Behavior and Codal Provisions

Wind engineering plays a vital role in the analysis and design of tall buildings, as wind is a highly variable and dynamic environmental load that interacts complexly with structural systems. Unlike static loads, wind exhibits fluctuations in speed, **দিশা**, and intensity, resulting in both mean and fluctuating pressure components acting on building surfaces. These pressures vary with height, terrain conditions, and surrounding obstructions, making accurate prediction of wind effects a challenging task. To standardize design practices, various codes and standards have been developed, such as IS 875 (Part 3):2015 in India, which provides guidelines for calculating wind speed, pressure, and load distribution on structures. However, these provisions are largely based on simplified assumptions and empirical relationships, which may not fully capture complex aerodynamic phenomena such as turbulence and vortex shedding in tall or slender structures (Holmes, 2015).

2.2 Height-Dependent Response

2.2.1 Displacement and Drift Variation with Height

The response of tall buildings to wind loads is strongly influenced by height, with displacement and storey drift being the most critical serviceability parameters. As building height increases, structural stiffness generally decreases, resulting in greater lateral flexibility. Consequently, lateral displacement increases nonlinearly along the height, reaching its maximum at the top storey due to cumulative deformation. Storey drift, on the other hand, tends to peak in

the mid to upper levels, where the combined effects of stiffness variation and lateral forces are most pronounced. Excessive drift can lead to structural damage and non-structural failures, making its control essential in design. Studies have consistently shown that taller structures require enhanced stiffness through appropriate structural systems to limit these deformations within permissible limits (Smith and Coull, 1991).

2.2.2 Dynamic Characteristics

The dynamic behavior of tall buildings is another important aspect of height-dependent response. As height increases, the natural frequency of the structure decreases while the fundamental time period increases due to reduced stiffness and increased mass participation. This makes taller buildings more susceptible to dynamic excitation caused by fluctuating wind forces. When the frequency of wind-induced forces approaches the natural frequency of the structure, resonance may occur, leading to amplified responses. Additionally, higher mode effects become significant in multi-storey buildings, influencing internal force distribution and overall behavior. These dynamic characteristics must be carefully evaluated to ensure structural safety and occupant comfort under wind loading conditions (Chopra, 2017).

2.3 Influence of Structural Systems

2.3.1 MRF vs Shear Wall vs Dual Systems

The choice of structural system significantly affects the wind response of reinforced concrete buildings. Moment Resisting Frame (MRF) systems rely on beam-column action to resist lateral loads but are relatively flexible, resulting in higher displacement and drift. In contrast, shear wall systems provide substantial lateral stiffness by acting as vertical cantilevers, effectively reducing deformation and improving overall stability. Dual systems, which combine moment-resisting frames with shear walls, offer a balanced approach by integrating stiffness and ductility. This combination enhances load distribution and reduces stress concentration, leading to improved performance under wind loading. Comparative studies have demonstrated that dual systems outperform individual systems in controlling lateral displacement and drift, making them more suitable for mid- to high-rise structures (Zhang and Gu, 2013).

2.4 Static vs Dynamic Wind Analysis

2.4.1 Limitations of Equivalent Static Method

The equivalent static wind load method is widely used in practice due to its simplicity and ease of implementation. It represents wind forces as static loads acting on the structure, which is adequate for low- to moderate-height buildings. However, this approach has several limitations when applied to taller or more flexible structures. It does not account for time-dependent effects such as gust fluctuations,

vortex shedding, and resonance, nor does it consider higher mode participation in multi-storey buildings. As a result, the static method may underestimate or overestimate structural response, leading to inaccurate design outcomes. Advanced dynamic analysis methods, which incorporate fluctuating wind forces and structural vibration characteristics, provide a more realistic representation of wind-induced behavior and are increasingly recommended for tall building design (Kareem and Kijewski, 2002).

3. METHODOLOGY

3.1 Prototype Building Description

3.1.1 G+16 Reinforced Concrete Building

The present study considers a typical mid-rise reinforced concrete (RC) building with a configuration of Ground plus 16 storeys (G+16). This height range is intentionally selected as it represents a transitional category where wind effects begin to significantly influence structural behavior. The building is assumed to be located in an urban environment and is representative of commonly constructed residential or commercial structures. The objective is to evaluate height-dependent wind response under realistic yet controlled conditions by maintaining uniformity in geometry and material properties across all analytical models.

3.1.2 Geometry, Plan Size, and Storey Height

The prototype building is modeled with a regular and symmetric plan to eliminate geometric irregularities and isolate the effect of structural configuration on wind response. A square plan of 20 m × 20 m is adopted, ensuring uniform load distribution and simplified analysis. Each storey is assigned a constant height of 3 m, resulting in a total building height of approximately 51 m. This regularity in geometry ensures that variations in results are primarily due to differences in structural systems rather than plan or elevation irregularities.

3.2 Material Properties

3.2.1 Concrete (M30)

Concrete is considered as the primary construction material for all structural elements, including beams, columns, slabs, and shear walls. In this study, M30 grade concrete is used, which is widely adopted in medium-rise construction due to its adequate compressive strength and durability. The modulus of elasticity is taken as 25,000 MPa, and the unit weight is assumed as 25 kN/m³. These properties directly influence the stiffness and mass of the structure, thereby affecting its response under wind loading.

3.2.2 Steel (Fe500)

Reinforcing steel of grade Fe500 is used to provide tensile strength and ductility to the structural elements. The

modulus of elasticity of steel is taken as 200,000 MPa, reflecting its significantly higher stiffness compared to concrete. The combination of concrete and steel ensures that the structure can effectively resist both compressive and tensile stresses, which is essential for handling lateral loads such as wind.

3.3 Structural Modeling

3.3.1 3D Finite Element Modeling in SAP2000

The structural analysis is performed using a three-dimensional finite element modeling approach in SAP2000. This software enables accurate simulation of structural behavior under various loading conditions. The entire building is discretized into finite elements, allowing for realistic representation of load transfer mechanisms and deformation characteristics. The use of 3D modeling ensures that both global and local responses of the structure are captured effectively.

3.3.2 Beam-Column Elements, Shell Elements, and Rigid Diaphragm Assumption

Beam-column elements are used to model frame members such as beams and columns, capturing their axial, shear, and bending behavior. Shear walls, where included, are modeled using shell elements to represent their in-plane and out-of-plane stiffness accurately. Additionally, each floor slab is modeled as a rigid diaphragm, assuming that it distributes lateral loads uniformly to vertical structural elements. This assumption simplifies the analysis while maintaining sufficient accuracy for evaluating overall structural response.

3.4 Structural Configurations

3.4.1 Model 1: Bare Frame (MRF)

The first model represents a conventional moment-resisting frame (MRF) system, where lateral loads are resisted solely through beam-column action. This model serves as a baseline for comparison due to its relatively low stiffness and higher flexibility.

3.4.2 Model 2: Central Shear Wall

In this configuration, a shear wall is introduced at the center of the building plan. The presence of a central core significantly enhances stiffness and provides a direct load path for lateral forces, reducing displacement and drift.

3.4.3 Model 3: Corner Shear Walls

This model includes shear walls located at the corners of the building. Such placement improves resistance to both lateral and torsional effects by providing better stiffness distribution across the plan.

3.4.4 Model 4: Dual System

The dual system combines the moment-resisting frame with shear walls, allowing both systems to share lateral loads. This results in improved structural performance by balancing stiffness and ductility.

3.4.5 Model 5: Optimized Model

The optimized configuration represents a refined structural arrangement in which shear walls and frame elements are strategically placed to achieve maximum efficiency. This model is expected to provide the best performance in terms of displacement control and overall stability.

3.5 Loading and Analysis

3.5.1 Dead Load and Live Load (IS 875 Part 2)

Dead loads include the self-weight of structural elements and additional permanent loads such as floor finishes and wall loads. These are automatically calculated based on material properties and section dimensions. Live loads, representing occupancy and movable loads, are applied as per IS 875 (Part 2) guidelines. These loads contribute to the overall mass and influence the structural response under lateral loading.

3.5.2 Wind Load (IS 875 Part 3:2015)

Wind loads are calculated according to IS 875 (Part 3):2015, considering factors such as basic wind speed, terrain category, height variation, and structural dimensions. The wind pressure increases with height and is applied as lateral forces in both principal directions of the building.

3.5.3 Equivalent Static Method

The analysis adopts the equivalent static wind load method, in which wind forces are represented as static loads acting on the structure. This approach simplifies the analysis while providing reasonable accuracy for mid-rise buildings. The loads are distributed along the height of the structure and applied at each floor level through diaphragm action.

3.6 Response Parameters

3.6.1 Lateral Displacement

Lateral displacement refers to the horizontal movement of the structure under wind loading. It is a key indicator of overall structural flexibility and is typically maximum at the top storey.

3.6.2 Storey Drift

Storey drift is defined as the relative displacement between two consecutive floors. It is a critical parameter for assessing

serviceability and must be controlled within permissible limits to prevent structural and non-structural damage.

3.6.3 Base Shear

Base shear represents the total lateral force transferred to the foundation. It reflects the overall demand on the structural system and is influenced by stiffness and load distribution.

3.6.4 Fundamental Time Period

The fundamental time period is a measure of the dynamic characteristics of the building, representing its natural vibration cycle. It is directly related to the mass and stiffness of the structure and plays a significant role in determining its response to wind loads.

4. RESULTS

4.1 Lateral Displacement

4.1.1 Variation Along Height

The analysis of lateral displacement reveals a clear height-dependent trend for all structural models. Displacement increases progressively from the base to the top of the building, following a nonlinear pattern. At lower storeys, the displacement remains relatively small due to higher stiffness and restraint conditions at the foundation level. However, as the height increases, cumulative flexibility and increasing wind pressure result in significantly larger lateral movements. The maximum displacement is consistently observed at the roof level, which reflects the cantilever-like behavior of multi-storey buildings subjected to lateral loads. This variation highlights the importance of controlling flexibility, especially in upper storeys where structural response becomes more pronounced.

4.1.2 Comparison Across Models

A comparative evaluation of the five structural configurations indicates substantial variation in displacement values depending on system stiffness. The bare frame (Model 1) exhibits the highest displacement due to its inherent flexibility and lack of dedicated lateral load-resisting elements. The introduction of shear walls in Models 2 and 3 significantly reduces displacement by increasing stiffness and providing direct load paths. Among these, corner shear walls perform better than centrally placed walls due to improved stiffness distribution. The dual system (Model 4) further enhances performance by combining frame action with shear wall resistance. The optimized configuration (Model 5) demonstrates the least displacement, confirming that strategic placement of structural elements is highly effective in controlling wind-induced lateral movement.

4.2 Storey Drift

4.2.1 Drift Profile

Storey drift shows a distinct variation pattern along the building height, differing from the displacement trend. Instead of increasing continuously, drift values follow a nonlinear distribution where they gradually increase from the base, reach a peak in the mid-to-upper storeys, and then slightly decrease toward the top. This behavior is attributed to the combined effect of stiffness variation and cumulative displacement along the height. The mid-height region experiences the highest relative deformation between consecutive floors, making it critical for serviceability considerations.

4.2.2 Maximum Drift Location

The maximum storey drift is generally observed between the middle and upper storeys of the building, rather than at the base or roof. This is a significant finding, as it indicates that the most critical region for potential structural and non-structural damage lies within this zone. The bare frame system shows the highest drift values, often approaching or exceeding permissible limits, while models incorporating shear walls demonstrate substantial reduction. The optimized and dual systems effectively control drift within acceptable limits, ensuring improved structural safety and serviceability performance.

4.3 Base Shear

4.3.1 Influence of Stiffness on Force Demand

Base shear represents the total lateral force transferred to the foundation and is strongly influenced by the stiffness of the structural system. The results indicate that stiffer structures tend to attract higher base shear compared to more flexible systems. This occurs because increased stiffness reduces deformation, thereby increasing the force demand resisted at the base. Consequently, models with shear walls and dual systems show higher base shear values than the bare frame system. While higher base shear may appear unfavorable, it actually reflects improved load resistance and structural integrity. Therefore, an optimal balance between stiffness and force demand is essential to achieve efficient and safe design.

4.4 Fundamental Time Period

4.4.1 Relation with Stiffness and Configuration

The fundamental time period is a key indicator of the dynamic characteristics of the building and shows an inverse relationship with structural stiffness. Flexible systems, such as the bare frame model, exhibit higher time periods due to their lower stiffness and greater deformability. In contrast, the inclusion of shear walls significantly reduces the time period by increasing rigidity. Among all configurations, the

optimized and dual systems demonstrate the lowest time periods, indicating superior stiffness and improved resistance to dynamic effects. This reduction in time period also implies reduced susceptibility to resonance under wind excitation, thereby enhancing overall structural performance.

5. CONCLUSION

The present study investigated the height-dependent wind response of a G+16 reinforced concrete building using five different structural configurations through three-dimensional finite element analysis. The results clearly demonstrate that wind-induced structural behavior is strongly influenced by both building height and structural system. Lateral displacement was observed to increase nonlinearly along the height, with maximum values occurring at the top storey due to cumulative flexibility and higher wind pressure. In contrast, storey drift exhibited a non-uniform distribution, with peak values located in the mid-to-upper storeys, highlighting critical zones for serviceability concerns.

Among the analyzed models, the bare frame system showed the highest displacement and drift, indicating inadequate stiffness for effective wind resistance in mid-rise buildings. The inclusion of shear walls significantly improved structural performance by enhancing stiffness and reducing deformation. Corner shear wall configurations proved more effective than central walls due to better stiffness distribution and reduced torsional effects. The dual system demonstrated further improvement by combining stiffness and ductility, while the optimized model provided the best overall performance.

Additionally, base shear was found to increase with structural stiffness, reflecting higher load resistance capacity, whereas the fundamental time period decreased with increasing stiffness, indicating improved dynamic behavior. Overall, the optimized structural configuration was identified as the most efficient system, offering a balanced performance in terms of displacement control, drift limitation, and structural stability under wind loading conditions.

5.1. Future Scope of Research

Future research can extend this study by incorporating dynamic wind analysis methods such as gust factor approach or time-history analysis to capture fluctuating wind effects and resonance behavior more accurately. Nonlinear material behavior, including cracking and yielding, should be considered to evaluate structural performance under extreme wind conditions. Further studies may explore a wider range of building heights and aspect ratios to establish generalized design trends. The inclusion of soil-structure interaction would provide a more realistic assessment of foundation behavior. Additionally, aerodynamic

modifications such as tapered or setback forms can be investigated for reducing wind effects. Experimental validation through wind tunnel testing and comparative studies using international design codes would enhance the reliability and applicability of the findings.

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