

A Review on Computational Methods for Evaluating Wind Effects on High-Rise Structures

¹Priyanshu Kumar Gandhi, ²Dr. Bikram Prasad.

^{1,2}Department of Civil Engineering, Lakshmi Narain College of Technology, Bhopal

Abstract: *Urban wind loads are a critical issue in the assessment of the structurally and economically coherent design and behavior of high-rise buildings within their environment. A precise study of wind effects on tall structures is highly essential in the design and analysis phase of high-rise buildings. Traditional methods, such as wind tunnel testing and other simplified analytical models, are widely used- but such methods are usually associated with exorbitant costs, time consumption, and inflexibility when considering a number of design configurations. With advancements in computational technology, such as powerful computing software and hardware along with computational tools, in place over the last few years, the computational method provides a much better alternative for analyzing the wind-induced behavior of tall structures. In this work, the broad range of mainstream and upcoming computer-based assessment strategies used to evaluate the influence of wind in tall buildings is put forward. This also includes an insight into numerical activities that involve Computational Fluid Dynamics (CFD) techniques, finite element models, and hybrid simulation methods, incorporating the results of actual experimental approaches. An investigation was also conducted to identify the effects of geometry, width, structural construction, and urban setting on pressure distribution and occurrence of wind-induced behaviors. The study also analyzed the pros and cons of different computational methodologies in terms of accuracy, computational efficiency, and applicability to engineering design. With the development of higher-performance computers and simulation algorithms over the past several years, a significant rise has occurred in the accuracy of computational tools in predicting wind loads. The review zeroes in on present trends in research and tackles the key challenges in modeling the highly complex aerodynamic interactions between wind flow and high-rise structures. Eventually, research recommendations on enhancing simulation accuracy and integrating computational techniques with structural optimization strategies have been put forth. This study is aimed at providing helpful information for both research-oriented and design-oriented engineers in the design and analysis of high-rise buildings against wind.*

Key Words: Wind Load Analysis, High-Rise Buildings, Computational Fluid Dynamics (CFD), Numerical Simulation, Structural Response, Wind Engineering, Tall Building Design

1. INTRODUCTION

An increase in the height of buildings will automatically bring increased amplitude in blasting of wind loads acting on the building, which will create yet another parameter to consider in the probable sway of the building. The outcome of wind loads in tall buildings is actual displacement or lateral deflection accompanied by vibrations or dynamic responses. Some of those may well enough be a serious safety or serviceability impact. Thus, the segregation of wind effects is vital for the reliable design and performance evaluation of tall buildings. Analyze wind loads with respect to some simplified engineering methods and empirical formulas provided in codes and standards [1]. However, they almost always failed to capture the intricate interaction between the wind flow and the tall building geometries, especially in the cases of irregular building shapes, the varying heights, and locating the buildings in urban areas. Hence, advanced computing techniques have proven to be effective tools for effectively predicting the wind-induced behaviour of tall buildings.

CFD, FEM, FDM, and wind tunnel simulation-based numerical analysis are used in studying wind flow patterns as well as pressure distribution in high resolution, while examining responses of the structure with utmost precision. Among others, they are employed here for the full simulation of aerodynamic aspects according to the forces like vortex shedding, turbulence, and separation all around buildings. Also, the contemporary features of computer tools make available a fusion of analysis that is structural and fluid dynamics to aid understanding of wind-structure interaction [2]. Recently, several studies have sought to improve the computational models, validate them experimentally, and apply them to relatively more complex high-rise buildings. Advanced simulation software and high-performance computation have given us yet another edge to the vulnerable environment. The aim of the review papers was to take a look at and summarize the existing methods of computational assessment for wind impacts on high-rise structures. It briefly discusses main technical methodologies, their positive and negative aspects, and highlights up-to-the-minute updates about simulation techniques that are currently used to analyze wind and tall buildings. The paper also brings out the identification of the knowledge gaps and future lines of

action so as to further improve computational methods for wind assessment with a high degree of reliability [3].

2. Wind Loads on High-Rise Buildings

The interaction between the wind and the tall building plays an important adoption in the RC detailing although it suffers quite a number from the wind-flow directions. Just like energy absorption in the tall buildings-every structure it is atop, absorbance, depending on the prevailing wind direction and wind speed. Different individual criteria should be applied for the building itself vs air dynamics (Aerodynamics vs. Thermodynamics), which is where a strategic range facilitates the designer to determine the necessary building layout. Since the proper layout lands would work to optimize the flow of wind owing to their swift flow in the surrounding air section. The world of aeronautics as an application of fluid dynamics studies has two types of flows in perfect conditions such as air standard atmospheres at sea level or in transonic region. A second essential application of fluid mechanics studied under the field of mechanics is the study of turbulence through either numerical techniques or experimentation. Wind-induced dynamic behavior is normally accountable for much more than the mere static force imposed by wind on a high-rise structure [4]. Tall buildings frequently emphatically act as the flexible cantilever rather than supporting any form of rigid cantilever. All this covers causes inertia moments through which the roughness of the building is percolated to the occupants' full acceleration and vibration forces-where vocation work is considered from the serviceability perspective rather than just static design issues. Wind modeling is typically routed through local building codes and standards-as IS 875 , ASCE 7, and Eurocode. Besides performing serviceability checks, these codes provide simple formulas and guidelines for calculating wind pressures based on the basic wind speed, local pressure, and building dimension. The quasi-static design approach adopted from code-based equations will be found insufficient in reflecting the complex aerodynamics observed with tall and/or highly irregular structures. To overcome these limitations, wind tunnel testing and computational simulations have become popular methodologies in advanced engineering practice. Consequently, with wind-tunnel testing, engineers can observe the airflow patterns and pressure distribution around scaled-down models of buildings. These experiments generally require sophisticated equipment and are usually prohibitively expensive and time-consuming [5].The figure 1 illustrates how wind flows around a high-rise building and generates dynamic forces on its surface. As wind strikes the

building, pressure differences form on the windward and leeward sides, leading to fluctuating loads and vortex shedding behind the structure. These dynamic wind effects can cause lateral displacement, vibrations, and structural sway, which must be carefully analyzed in the design of tall buildings to ensure stability and safety.

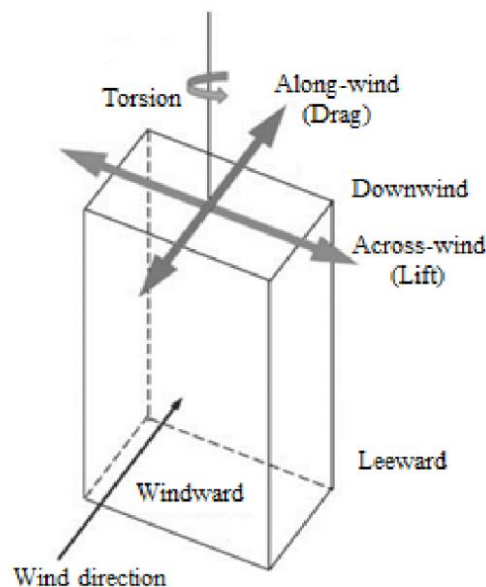


Fig -1: Dynamic Wind Loads Effects on High-Rise Buildings [5]

In the recent decade or so, the computational method has become not only popular but increasingly necessary for the analysis of wind effects upon tall buildings. CFD analyses are of great value in evaluating wind flow, turbulence, and pressure distribution around torsionally irregular structures with high precision. These are insightful tools when it comes to the discussion of aerodynamic behavior and design-tune structural shapes to lessen the influence of wind forces. Assessment of wind load is needed to ensure safety structurally and improve building performance and sustainability. By understanding its behavior and interaction with high-rise structures engineers can enhance their ability to design advanced high-rise buildings that can withstand excessive environmental conditions and at the same time provide occupant comfort. Table 1 presents the major characteristics of wind flow around tall structures, highlighting how variations in wind speed, pressure distribution, turbulence, vortex formation, and surrounding building interference influence the aerodynamic behavior and structural response of high-rise buildings [6].

Table -1: Characteristics of Wind Flow Around Tall Structures

Characteristic	Description
Wind Speed Variation with Height	Wind speed generally increases with height due to reduced surface friction, resulting in higher wind pressures on upper floors of tall buildings.
Windward Pressure	The side of the building directly facing the wind experiences positive pressure as the wind force impacts the surface.

Leeward Suction	The opposite side of the building experiences negative pressure or suction due to the separation of airflow behind the structure.
Side Pressure Effects	Wind flowing around the sides of a building produces lateral pressure variations that can influence structural stability.
Vortex Shedding	Alternating vortices form behind the building as wind flows past it, which can induce oscillations and dynamic vibrations in tall structures.
Turbulence Effects	Irregular wind fluctuations caused by surrounding buildings, terrain, and obstacles lead to turbulent airflow around tall structures.
Flow Separation	Wind flow detaches from sharp building edges, creating wake regions with reduced pressure and complex airflow patterns.
Interference Effects	Nearby buildings can alter wind patterns, causing amplification or reduction of wind forces on the structure.

3. Impact of Wind Loads on Structural Performance

Wind loads significantly impact the structural behavior and performance of high-rise buildings. In contrast to low buildings, tall buildings are under a greater risk of amplified forces, created by wind, as a result of their increased heights and slenderness: which includes displacements, internal stresses, and vibrations that are detrimental to both the safety and serviceability of the structure. One of the most obvious effects of wind loading on buildings is lateral displacements attributable to the wind [7]. As the wind strikes the building surface, the latter sways with the wind. Any excessive lateral movement can result in structural instability or damage to non-structural elements like walls, windows, and cladding systems. Therefore, by design, engineers opt for stronger structural systems like braced frames, shear walls, and tube structures to counter lateral wind forces effectively.

Also, one of the dynamic responses seen in high-rise structures is due to the wind forces acting upon the building. High-rise structures will present a greater flexibility, leading to a situation of the oscillation generated by the shedding of vortices, which is mixed with the effects of the turbulent flow. The development of some oscillations resonating with wind-induced forces could significantly amplify the vibrations and fatigue loads of the structures provided the frequency of wind forces is close to the natural frequency of the building. Occupant comfort should not be neglected. Even if the structural integrity of a building is secure, excessive building movement due to the wind force can make occupants uncomfortable or even cause motion sickness [8]. Hence there are established serviceability limits on permissible acceleration and displacement of tall buildings.

Wind loads also dictate how structural design and selection of material work. There is the necessity of reflecting both wind-energy pressures and the material behavior while calculating the size and strength of the structural components. For bearing extreme wind conditions, materials having greater strengths and efficient structural systems must be selected most often.

Let me indicate that wind loads, to some extent, govern foundation stability as well as load distribution inside the structure: wind-induced movement could result in overturning moments that produce extra stresses at the base of the building, possibly requiring stronger foundation systems [9]. Therefore, understanding wind loads and their effect on structural systems is essential for designing tall buildings that are safe, durable, and comfortable. The availability of advanced computational analysis and sophisticated structural design techniques helps engineers in mitigation of wind-related effects and in enhancing the resilience of tall structures.

4. Computational Methods for Wind Analysis

High-rise building analysis with respect to wind effect has drastically improved as computational techniques progress. Traditional analytical methods and empirical formulas following the building codes employ a somewhat facile approach to wind loads estimation. Methods so stepwise applied at odds with the complex aerodynamic behavior displayed in tall and irregularly shaped structures. The advent of computational methods has opened new avenues for the study of wind-flow patterns, pressure distributions, and, subsequently, the structural responses in the modern high-rise building. Wind analysis includes the use of computational techniques to mimic wind interactions with structural systems by means of numerical algorithms and computer simulations. This approach enables engineers and researchers to foresee how wind forces would affect buildings under different environmental conditions. The primary strength of computational methods lies in the ability to study complex geometries, natural environments, and dynamic wind conditions more carefully than conventional techniques. Computational Fluid Dynamics (CFD) has been one of the widely used computational approaches [10]. The CFD technique is used to model the airflow around structured objects, in solving the mathematical equations governing the motion of the fluid. Wind flow patterns can be clearly identified, areas of high pressure or turbulence can be detected, and the aerodynamic performance can be evaluated from CFD modeling. Designers make a valuable use of such a technique to analyze their irregular building designs and complex urban environments within parameters of virtually unpredictable wind flows. In the context of

structural response to wind forces, the Finite Element Method (FEM) is a major computational approach for understanding building responses. The FEM method breaks down the building into smaller elements and then calculates the stress, strain, and displacement of each element due to the enforced loads of the wind. Engineers may carry out studies that encompass both the aerodynamic behavior and structural performance of the structure relevant to its wind load using models of CFD and FEM together. Besides CFD and FEM, there are many other numerical methods such as Finite Difference Method (FDM) and boundary element methods used in wind engineering. These methods are satisfactory to solve the differential equations for fluid dynamics or structural dynamics. The modern computational tools integrate various simulation software available, such as ANSYS, OpenFOAM, and ETABS, that allow for a detailed modeling of wind-structure interaction [11]. These tools nicely visualize pressure contours, flow patterns, and structural deformations, which provide the engineer with an easier way to comprehend and thereby implement improvements on the subsequent wind-induced design strategies of buildings. Predominantly, computational techniques have now become indispensable for contemporary wind engineering methodologies. The motivation is to facilitate intricate simulations, alleviate the need for pricey wind tunnel testing, and make it easier to shape buildings with strong emphasis towards a better aerodynamic performance. Given that increasing scientific data computations are vital, computer methodologies are becoming more prominent towards reducing computational charges for structural design and analysis in the realm of high-rise safety and efficiency.

4.1 Computational Fluid Dynamics (CFD) Techniques

Computational Fluid Dynamics (CFD) involves advanced computational techniques that are widely used to analyze wind flow around high-rise buildings. This typically involves solving the governing equations of fluid motion, especially in solving the Navier Stokes equations. In so doing, engineers can simulate complex airflow patterns, pressure distribution, turbulence, and vortex formation that occur when wind interacts with tall structures. The series of steps required for a CFD investigation typically involve creating a three-dimensional geometric model of the building and its surroundings, generating a computational mesh which discretizes the region up into smaller cells, and defining boundary conditions, such as wind speed, direction, and turbulence intensity [12]. Once the model has been produced, numerical solvers compute airflow behavior through the region, and post-processing tools visualize the result showing velocity vectors, pressure contour, and streamline patterns. These visualization techniques allow geographic engineers to pinpoint regions of high wind pressure, assess the aerodynamic performance of buildings, and hence, suggest possible improvements. CFD indeed has a great advantage in that it can be used to solve complex building geometries and

urban environments while enabling multiple simulations for design optimization under changing wind conditions. However, the accuracy of the results produced by the CFD largely depends on mesh quality, turbulence modeling, and computational resources, with high-resolution simulations requires significant processing times. However, despite having such drawbacks, CFD has become a prominent tool for modern wind engineering main goal enhance in providing more accurate predictions of wind effects in terms of the edifice at hand and improving the hydra-safety and efficient design of tall buildings [13].

5. Finite Element and Numerical Simulation Methods

In the structural engineering realm, methodologies like finite elements like to be frequently employed for deliberation on matters concerning wind-force-exposed tall buildings. Such approach usually helps in investigating structural reactions in a sequential and coherent manner of distribution of stress, each deform as a result of an action of vibrating regime within the system, and overall stability. The Finite Element Method consists of a structure korpus orthogonally differentiated into numerous relatively small interconnecting elements such as beams and shells governed by suitable equations which depict respective mechanical characteristics [14]. By application of the wind loads, such a set-up linked to the involved mathematical machinery calculates the stresses, strains, and displacements for each element, hence informing the engineer about how the wind forces are transmitted to different elements such as the columns, beams, bracings, and shear walls in real-life structural systems. These give conventive studies for dynamic calculations, an added advantage, through which the simulation of variable wind loads due to turbulence and vortex shedding or internal vibrations and oscillations under the aegis pertain between a considerably tall building of high-rise configuration structure that reaches even dynamic behavior if the sequence of naturality f_0) were to be computed, for example, that of damping ratio. Whereas to maintain a predictive approach to the dynamic behavior of the structure, the frequency must be maintained within the examine as velocities within wind-induced motions. Additional methodologies similar to the FEM are the Finite Difference Method (FDM) and Boundary Element Method (BEM) for solving equations in relation to structural problems and fluid flows. Modern engineering software like ANSYS, SAP2000, STAAD Pro, and ETABS brings these numerical simulations together to study wind loading benchmarking further on structural performance. These tools offer parametric studies where the engineer is given a chance to change any design parameter and hence analyze an optimized configuration. While simulation-based approaches grant detailed and accurate results, the accuracy level of the information largely depends on model assumptions and their validation against experimental or field data [15]. Eventually, then, the finite element and numerical simulation outline an essential technique and tool in theoretical and design framework application to high-rise

buildings, furnishing the engineer with their module to develop structures on a higher hierarchical plane, safer, efficient, and resistant to wind loads.

5.1 Modeling and Simulation of Wind-Structure Interaction

Wind-structure interaction (WSI) is the combination of movements and airflow patterns within the wind, the building, and their response to each other. A continuous flow stream on a building template causes some pressure patterns as well as promotes vibration. The performance-based design of tall buildings does depend on reliable simulation-based approaches in this Infomed era to try to engage both fluid dynamics either with the structural analysis viewing panes for how wind loads affect displacement, vibration, and stress distribution at different environmental conditions. Aerodynamic modeling is an ongoing application of Computational Fluid Dynamics (CFD) or wind tunnel experiments because wind flow around this particular kind of building is modeled so that recognition of any collapse even in strategic locations can be duly addressed. Structural modeling by numerical means, such as Finite Element Method (FEM), provides a valid insight as verbal extension to various factors considering the influence of aerodynamic forces to unoccupied and consumed vibrations, as well as the final results mainly from this interrelationship [16]. Wind-structure interaction can be fluorinated into static interaction, built upon steady wind forces, and dynamic interaction, which takes into account fluctuating wind loads as a result of turbulence and vortex shedding that may alter the concept of vibrations and occupant comfort. Modern tools like ANSYS, OpenFOAM, and ETABS embed aerodynamic and structural analyses into coupled simulations to gain better understanding of wind behavior and structural response. With an available set of potentially massive models with various settings of designing alternatives, geometry optimization, and eventually which minimizes wind-induced structural support and stability would always precede construction. Still, to have a last successful fall, accurate modeling of wind-structure interaction must provide for good input parameters suitable constraints and experimental validation for reliable results. By and large, wind and pertaining modeling and simulation work will pave the way for the design of tall buildings in a safe and efficient manner, which in its turn will quickly resist harsh environmental wind forces [17].

5.2 Aerodynamic Modeling of High-Rise Buildings

Aerodynamic modeling plays a vital role in understanding how wind flows around high-rise buildings and how this interaction influences structural performance and safety. As the height of buildings increases, the aerodynamic behavior of wind becomes more complex due to variations in wind speed with height, turbulence effects, and flow separation around building surfaces. Accurate aerodynamic modeling enables engineers to evaluate wind pressure distribution, airflow patterns, and potential aerodynamic instabilities that may affect the structural stability and serviceability of tall

buildings. When wind approaches a high-rise structure, it interacts with the building surfaces and produces several aerodynamic phenomena such as stagnation pressure, flow separation, vortex shedding, and wake formation [18]. The windward face of a building experiences positive pressure because the wind directly impacts the surface, while the leeward side experiences negative pressure or suction due to airflow separation and the formation of wake regions behind the building. In addition, the side surfaces of the building experience fluctuating pressure distributions as wind flows around the structure. These aerodynamic forces generate lateral loads and dynamic effects that must be carefully considered in the structural design of tall buildings. Aerodynamic modeling helps engineers predict these wind-induced forces by simulating the airflow behavior around the building and evaluating how the structure interacts with surrounding wind conditions. Traditionally, wind tunnel testing has been widely used to analyze aerodynamic characteristics by testing scaled models of buildings under controlled laboratory conditions. These experiments allow researchers to measure wind pressure distribution, turbulence intensity, and vortex formation around structures, providing valuable insights into wind behavior. However, wind tunnel testing can be costly, time-consuming, and limited in its ability to test multiple design variations quickly. With the advancement of computational technology [19].

5.3 Structural Response Simulation under Wind Loads

Structural response simulation under wind loads is an important aspect in the design and analysis of high-rise buildings... As an essential step, wind-force-based lateral force leads, affecting the building structure with horizontal forces; essentially, wind loads cause horizontal displacements, internal stresses, and vibrations within the building. To predict how the structure will behave under different wind conditions, engineers need to make use of structural response simulation so as to ensure that a structure does not pose unsafe structures for its occupants at any time. One of the methods widely used for this analysis is Finite Element Method (FEM), whereby the building is divided into some smaller interconnected elements such as beam, column, and slab [20]. After being assigned corresponding material properties, elements are meant to meet given physics equations appropriate to their mechanical behaviours under loading conditions. At the time of wind application in the simulation model, the system calculates the stresses, strains, and displacement due to the forces acted across the structural elements. Besides the static analysis, stoic analyses cover the dynamic effects arisen from the wind as loads fluctuate because of turbulence or vortex shedding. These variations in wind pressure can cause vibrations and oscillate taller buildings, and if these frequencies match the natural frequency of the structure, resonance may occur that amplifies the motion of the structure. To evaluate these effects, engineers conduct modal analysis and time-history analysis, which identify natural frequencies, damping characteristics, and vibration modes of the building. Modern software used for structural analysis, such as ETABS,

SAP2000, STAAD Pro, ANSYS, allow for such detailed simulation of structural responses against wind loads being necessary and directed by the governing building code or mapped from wind tunnel tests and related fluid flow software. Moreover, these simulations elicit response with regard to such factors of serviceability as building sway and accelerations that have indelible influence on occupant comfort. Engineers can refine and optimize the structural design and add dampers, ensuring resilience against wind forces while maintaining the structural integrity and leading to an economically viable, long-lasting performance [21].

6. Comparative Analysis of Computational Techniques

High-rise buildings experience strong wind force, making the exploration and analysis of wind effects on high-rise buildings an area of increasing importance. Hazardous wind loads affect the structural stability, serviceability, and dwelling comfort of tall buildings. Consequently, wind loading on high-rise structures continues to be a scientific focus of investigation. Attention has been heightened on the aerodynamic behavior, structural response, and advanced computational methods for the enhancement of performance of high-rise structures subject to wind loading. Both experimental and numerical investigations have brought to light the fact that the aerodynamic design of tall buildings significantly influences wind pressure distribution and structural stability. Experimental studies have pointed to design possibilities, in wind load reduction, focused on the geometries of high-rise structures, including modifications in wind load minimization due to the change in wind flow due to formation of vortex shedding effects [1]. These designs contribute in reducing vibrations in the structure and improving general structural performance. Further development in computational modeling has significantly enhanced the capacity to study complex aerodynamic interactions due to buildings being placed in dense urban environments. AI models have been introduced to increase the fulfilment of aerodynamic interference predictions between adjacent, operating buildings. Explainable AI models have been deployed in predicting wind forces and aerodynamic interference in complex high-rise building clusters by providing qualitatively interpretable inferences on influencing factors that affect wind behavior [2]. They enable engineers in understanding how different urban configurations affect the flow and distribution of wind-induced forces on buildings.

New vibration control devices have been coined for tall structures. The nonlinear energy sinks lead to various pilot-scale studies to suppress wind-induced vibrations in high-rise buildings. This passive control system can ideally absorb the vibrational energy and safeguard the primary structure from damage, moving most of the energy down to the secondary devices during wind-induced remove excitation. These new advanced control mechanisms help significantly in improving the dynamic stability of tall structures. Studies

have also been carried out to improve the effectiveness of high-rise steel buildings performance under dynamic environmental loads by employing two-dimensional beams or frames with bracing structures. According to research conducted on optimum structural design, in combination, special moment frames and a bracing system will markedly improve the structural performance in response to wind as well as earthquake forces. Through optimization algorithms, the configurations min-mass configurations to the characteristic safety parameters [12]- are approximated.

Structural analyses in connection with modeling developments are also emerging. A neural network-based approach rates current displacement fields in ultra-high-rise structures under non-linear seismic loading for operational prediction. Such deep learning models may be in a position to provide quick approximations of structural responses, thereby proving extremely advantageous for real-time structural health monitoring and real-time prediction [13]. Indeed, these intelligent methods can be extended to the forecasting of the wind-in-wind-on-structures problem in this area. The wind load on a curtain-wall façade, as it interacts with building aerodynamics and interference effects, can considerably affect the vulnerability of this type of façade system. Vulnerability assessments prove that the wind-induced pressure caused by wind-induced pressures may cause a rupture in curtain-wall systems if the proper strength and stiffness cannot resist the aerodynamic forces [14]. Hence, each façade design must integrate precise wind-loading analysis for structural security.

The architecture's layout has a significant influence on the dynamic response of buildings when excited by wind. Studies on tall buildings with X-shaped plans have shown that such forms exhibit distinct vibration characteristics under wind loading. The dynamic response of such buildings depends on their structural stiffness, mass distribution, and wind flow interaction with aerodynamics [15]. These results underscore the importance of considering the architecture layout during the design of the structure. In the description of the A. I. Research, the executed projects are about adaptive, resilient systems; dealing with dynamic networks. Other advanced strategies include dampening systems, adaptive controls, and brace configurations primarily to enhance the resilience of sky-rise structural systems. These integrated methodologies are rooted in the foundation of structural engineering alongside smart control technologies gearing their potential to help improve the performance of tall structures subjected to wind-induced loads [16]. Also, aerodynamic optimizations of the tall buildings have been studied a lot to make them work well under high wind speeds. Wind tunnels studies have demonstrated that the modification of building shapes can enormously minimize wind load and reduce vibrations of the structure. These different measures in aerodynamics would help in reducing vibration stresses and enhancing the comfort levels of residents during periods of high wind [17].

Wind-based engineering has become a crucial criterion for opting for applicable structural configurations in tall high-rise reinforced concrete buildings. The technical concept is

centered on the evaluation of structural performance under the influence of numerous wind loading scenarios in order to eventually select the best-suited structural form. The concept not only helps in optimizing the building design but also in economizing it by taking into consideration the load conditions or life safety issues in the early design phase by considering the effects of its interaction with the construction material [18]. From the prior reviews, the conclusions arrived at are those citing wind effects on high-rise buildings being complex consequences of interaction among aerodynamic forces, structural behavior, and moving urban environmental factors. The experimental techniques, computational simulations, artificial intelligence, and structural control systems used in this work have increased the understanding of wind-structure interaction. What to do in the near future, however, will be to consider combining advanced modeling

techniques and the application of diversified design strategies, such as a sustainable design, as well as novel methods in mechanical vibration control, to further enhance the seismic response of a high-rise structure in fast urban growth.

Table 2 summarizes the comparison of different methods for analyzing wind effects on high-rise buildings, showing that experimental and hybrid testing provide the highest accuracy but are resource-intensive, CFD offers a balance between accuracy and computational effort, AI-based predictions are highly efficient with slightly lower accuracy, and damping systems effectively reduce vibration with moderate effort. Table 3 presents the major advantages and limitations of various existing methods used for evaluating wind effects on high-rise buildings.

Table -2: Accuracy and Efficiency of Different Methods

Method / Approach	Estimated Accuracy (%)	Computational / Experimental Efficiency	Remarks	References
Experimental wind tunnel tests (helical building)	98%	Low – time-consuming, setup-intensive	Provides realistic aerodynamic load data; considered benchmark	[1]
CFD simulations (rectangular & C-shaped buildings)	92%	Moderate – faster than experiments, but computationally intensive	Accuracy depends on mesh quality, turbulence model, and boundary conditions	[4]
AI-based prediction of aerodynamic interference	88%	High – real-time once trained	Fast predictions; good correlation with CFD or experimental data	[2]
Hybrid shake table-wind tunnel testing (seismic + wind)	99%	Low – highly resource-intensive	Captures coupled wind-seismic effects accurately; ideal for extreme events	[6]
Pre-tensioned nonlinear energy sinks / damping systems	93%	Moderate – requires prior calibration	Effective for reducing vibration and improving occupant comfort	[11]

Table-3: Advantages and Limitations of Existing Approaches

Aspect	Advantages	Limitations / Challenges
Experimental Analysis	High accuracy in capturing real wind and seismic effects	Cannot be used in real-time; setup is complex and time-consuming
CFD & Numerical Simulations	Can model complex geometries (C-shaped, X-shaped, helical) and airflow patterns	High computational cost; results depend on mesh and solver settings
AI & Machine Learning Approaches	Rapid prediction of displacement, vibration, and aerodynamic interference; interpretable models	Requires large datasets; may be site-specific; limited generalization
Aerodynamic Optimization	Reduces wind-induced forces; improves occupant comfort and structural performance	May conflict with architectural or material constraints
Structural Control Systems	Reduces vibration and enhances dynamic	Increases structural complexity

(Dampers, Bracing, Adaptive Control)	resilience	and maintenance requirements
Urban Interference Assessment	Predicts wind effects in dense urban areas; assists urban planning	Sensitive to surrounding layout; may not generalize to other sites
Performance-Based Optimization	Selects efficient structural systems for both wind and seismic loads; reduces material usage	Limited applicability for extreme wind events; requires accurate modeling

7. CONCLUSION AND FUTURE WORK

This paper highlights the importance of evaluating wind effects on high-rise buildings using advanced computational and experimental approaches. As urban development continues to rise and grow tall, the aerodynamic behavior of rising structures has become a vital consideration for the design of secure structures, which has implications for stability and comfort of inhabitants. Wind behavior on high-rise buildings is very complex because of turbulence, vortex shedding, and varying pressure patterns for each surface of the building. Therefore, accurate assessment of wind forces on these structures is critical for the design of tall structures of today. On the one hand, there is an enormous record on the area of computational techniques applied to the analysis of wind-structure interaction, like CFDs, numerically simulated design experiments and structural response models. But these computational apparatuses provide a broader spectrum of opportunities with regards to the flexibility along with faster analysis, thus permitting the simulation of various alternative configurations under varying external conditions, compared to the traditional way of carrying out wind tunnel tests. Simultaneously, these methodologies assist the engineer in a more precise prediction about the air and wind pressure distribution, the air flow pattern, and various onsets of structural responses. Furth more, research should be aimed at improving the accuracy of these simulations, integrating the latest modeling techniques, as well as formulating more efficient analytical procedures for the understanding of wind-structure interaction to support some safer and sustainable design of tall structures

REFERENCES

- [1] Han, Kanghui, Guohui Shen, and Shice Yu. "Experimental investigation on the reduction of wind loads on helical high-rise buildings under atmospheric boundary layer." *Journal of Wind Engineering and Industrial Aerodynamics* 271 (2026): 106395.
- [2] Deng, H. C., et al. "Explainable AI-driven prediction and interpretation of aerodynamic interference effect in complex high-rise building clusters." *Advances in Engineering Software* 215 (2026): 104121.
- [3] Xu, Haiwei, et al. "Interference effects of aerodynamic forces for high-rise buildings with different side ratios." *Engineering Structures* 356 (2026): 122431.
- [4] Tyagi¹, Shikha, Ritu Raj, and Shilpa Pal. "Effect of Wind on High Rise Rectangular Building by CFD Simulations." *International Conference on Sustainable Planning, Architecture and Civil Engineering (SPACE 2026)*. Allied Publishers, 2026.
- [5] Liu, Can-Hua, Hong-Nan Li, and Chao Li. "Experimental Evaluation of Coupled Seismic-Wind Load Effects on the Antenna Mast Atop Super High-Rise Structures via Hybrid Shake Table-Wind Tunnel Tests." *Earthquake Engineering & Structural Dynamics* (2026).
- [6] Vargiomezis, Themistoklis, and Catherine Gorlé. "Predicting wind-induced interference effects on a low-rise building in a realistic urban area using large-eddy simulations." *Journal of Wind Engineering and Industrial Aerodynamics* 268 (2026): 106270.
- [7] Kumar, Parveen, et al. "Analysis of wind effect surrounding the C-shape high-rise building." *Computational Mathematics in Engineering: Proceedings of ICCMA 2025* (2026): 171.
- [8] Patel, Grishma M., and Suhasini Kulkarni. "Investigation of viscoelastic coupling damper (VCD) behaviour developed from natural rubber using experimental and computational methods." *Asian Journal of Civil Engineering* (2026): 1-20.
- [9] Deng, Qirui, et al. "Integrated numerical modeling strategies for tree-wind interactions: a review and proposed assessment framework for resilient urban design." *Urban Forestry & Urban Greening* (2026): 129353.
- [10] Li, Jinyu, et al. "Wind Vibration Control in High-Rise Buildings Using Pre-tensioned Nonlinear Energy Sink: Experimental and Numerical Study." *Journal of Building Engineering* (2026): 115488.
- [11] Goodarzimehr, Vahid, Amirali Barzegari, and Nader Fanaie. "Optimal design of high-rise steel structures using special moment frames and bracing systems under dynamic wind and seismic loads." *Engineering Optimization* (2026): 1-33.
- [12] Zhang, Shuxiang, et al. "Improved Inception-based Neural Network for Real-time Prediction of Displacement Field in Nonlinear Seismic Response of Ultra-High-Rise Structures." *Journal of Building Engineering* (2026): 115662.
- [13] Yadav, Himanshu, and Amrit Kumar Roy. "Wind Induced Vibration and Dynamic Response of Tall X-Shaped Plan Building." *Journal of Vibration Engineering & Technologies* 14.1 (2026): 39.
- [14] Aly, Aly Mousaad. "Beyond Stiffness: Architecting Dynamic Resilience in High-Rise Structures through

- Advanced Damping, Adaptive Control, and Bracing Synergy." (2026).
- [15] Yadav, Himanshu, and Amrit Kumar Roy. "Aerodynamic Performance Optimization of High-Rise Structures Under Extreme Wind." *Journal of Building Engineering* (2025): 114364.
- [16] Hasrat, Hussin Ahmad, and Mohit Bhandari. "Performance-Based Wind Analysis for Optimal Structural System Selection in High-Rise Reinforced Concrete Buildings." *Journal of Vibration Engineering & Technologies* 13.1 (2025): 85.
- [17] Miao, Yijia, and Stephen Siu Yu Lau. "Effect of Linear Building Blocks on the Wind Environment of Streets between High-Rise Buildings A case of Hong Kong." *International Review for Spatial Planning and Sustainable Development* 11.3 (2023): 63-77.
- [18] Li, Qian, et al. "Impact of planar area ratio and opening positions on natural cross ventilation performance in sheltered high-rise buildings: A simulation study." *Building and Environment* 245 (2023): 110889.
- [19] Zhou, Qi, et al. "Improvement of GPS displacement measurement accuracy for high-rise buildings by machine learning." *Journal of Building Engineering* 78 (2023): 107581.
- [20] Alnajjar, Sonia & Al-Azhari, Wael. (2021). "Review of Aerodynamic Design Configurations for Wind Mitigation in High-Rise Buildings: Two Cases from Amman." *Civil Engineering and Architecture* 9. 708-720. doi:10.13189/cea.2021.090313.
- [21] Zhou, Qiang, et al. "Vulnerability Assessment of High-Rise Glass Curtain Walls under Wind Loads with Building Interference Effects." Available at SSRN 6169938.