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Evaluating the Impact of Wind Vibrations on Building Structures - A Review

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Abstract: With the continuous growth of urbanization and the rapid development of high-rise and slender building structures, wind-induced vibrations have emerged as a governing design concern in modern structural engineering. Unlike conventional gravity and seismic loads, wind action is stochastic in nature and can induce significant dynamic responses even at moderate wind speeds, affecting both structural safety and occupant comfort. Wind-induced vibrations can lead to excessive lateral displacements, accelerations, fatigue damage, serviceability failures, and psychological discomfort among occupants, particularly in tall, lightweight, and flexible buildings. This review paper presents a comprehensive evaluation of wind-induced vibrations in building structures, focusing on their generation mechanisms, structural response characteristics, serviceability implications, and mitigation strategies. The paper synthesizes findings from experimental investigations, numerical simulations, full-scale monitoring studies, and recent review articles. Special emphasis is placed on human comfort, cognitive performance degradation, aerodynamic modification, structural control devices, podium effects, timber buildings, and emerging performance-based design approaches. The review highlights the limitations of conventional code-based methods and underscores the need for integrated aerodynamic, structural, and human-centric design frameworks. Finally, critical research gaps are identified to guide future studies toward safer, more resilient, and occupant-friendly building designs.

Keywords: Wind-induced vibration, Tall buildings, Structural dynamics, Occupant comfort, Serviceability, Aerodynamic optimization, Vibration control, Performance-based design

I. INTRODUCTION

In recent decades, the global construction industry has witnessed a remarkable increase in the number of tall, slender, and architecturally complex buildings driven by rapid urbanization, land scarcity, and economic growth. High-rise buildings are no longer confined to metropolitan centers but are increasingly being developed in medium-sized cities worldwide. While advancements in material technology, construction methods, and computational tools have enabled the realization of such structures, they have also introduced new challenges related to structural dynamics and serviceability performance. Among various environmental loads acting on buildings, wind load plays a unique and critical role. Unlike static gravity loads, wind loads are highly variable, random, and time-dependent. Wind-induced forces can excite building structures dynamically, resulting in vibrations that may not necessarily threaten structural collapse but can significantly impair serviceability and occupant comfort. Excessive vibrations may cause motion sickness, anxiety, reduced productivity, and in extreme cases, long-term psychological stress among occupants. Traditionally, structural design has focused primarily on ensuring strength and stability under extreme wind events. However, it has become increasingly evident that serviceability considerations—particularly acceleration limits and human comfort—often govern the design of tall buildings. Many modern structures satisfy strength requirements yet fail to meet comfort criteria under relatively frequent wind conditions.

Wind-induced vibrations arise due to complex aerodynamic phenomena such as buffeting caused by atmospheric turbulence, vortex shedding due to flow separation, and self-excited mechanisms including flutter and galloping. These effects become more pronounced in tall, flexible, and lightweight structures, such as steel and timber high-rise buildings. Furthermore, architectural features like setbacks, podiums, irregular shapes, and façade elements significantly influence wind–structure interaction. Recent research has expanded beyond traditional structural response analysis to include occupant perception, cognitive performance, economic implications, and life-cycle performance. With the growing emphasis on sustainability and performance-based design, understanding and mitigating wind-induced vibrations has become an essential aspect of modern civil engineering practice. This review paper aims to systematically evaluate the current state of knowledge related to wind-induced vibrations in building structures, highlighting advancements, limitations, and future research directions.

II. LITERATURE REVIEW

2.1 Effect of Wind-Induced Vibrations on Occupants' Work Performance

Heshmati et al. (2025) conducted one of the most comprehensive experimental investigations into the impact of wind-induced vibrations of tall buildings on occupants' cognitive and work performance. Using the VSimulator motion platform at the University of Bath, the researchers replicated realistic wind-generated building motions and examined their influence on human cognitive functions. A structured psychological test framework was developed to evaluate attention span, memory retention, executive function, and subjective work efficiency under varying acceleration amplitudes and vibration frequencies. The study revealed a direct and quantifiable relationship between vibration intensity and cognitive degradation. Within an acceleration range of 0–0.1 m/s², every 0.1 m/s² increase resulted in approximately a 0.2 standard deviation reduction in cognitive ability and a 0.5-unit decrease in perceived work efficiency. Additionally, increasing vibration frequency within the 0–0.5 Hz range further amplified performance deterioration. Importantly, the results demonstrated that even vibration levels near or below human perception thresholds can negatively affect productivity. This research represents a critical shift from traditional comfort-based vibration criteria toward performance-based serviceability limits, emphasizing the necessity of incorporating human work efficiency into tall-building vibration design guidelines.

2.2 Wind-Induced Vibration Serviceability of Multi-Storey Timber Buildings

Kurent and Brank (2025) investigated wind-induced vibration serviceability in ten multi-storey timber and hybrid timber buildings across Europe, with heights ranging from 22 m to 74 m. Due to their lightweight nature and lower inherent damping, timber buildings are particularly susceptible to wind-induced accelerations. The study evaluated occupant comfort by computing peak accelerations using EN 1991-1-4:2005 wind loading provisions and assessing them against ISO 10137 serviceability criteria. The parametric analysis highlighted that geographical location and local wind climate significantly influence predicted peak accelerations. Among architectural parameters, rounded edge radius exhibited the strongest effect on vibration performance, underscoring the importance of aerodynamic shaping. Structural modification studies revealed that increasing stiffness was more effective in shorter buildings, whereas increasing mass was more beneficial for taller timber structures due to their higher flexibility. The evaluation of the world's tallest timber building demonstrated that acceptable comfort levels can be achieved through aerodynamic optimization and performance-based dynamic design. The authors concluded that wind-induced acceleration, rather than structural strength, often governs the design of tall timber buildings.

2.3 Numerical Simulation of High-Rise Buildings with Podium Structures

Jiang et al. (2025) presented a numerical investigation into wind-induced vibration responses of high-rise buildings integrated with podium structures, which are commonly adopted in modern commercial and mixed-use developments. The authors developed a fast prediction algorithm using the autoregressive (AR) method to generate fluctuating wind speed time histories and corresponding wind loads. The accuracy of the generated wind spectrum was validated against target spectra. Using MIDAS GEN software, eleven structural configurations were analysed to evaluate the influence of podium presence, height, area, and layout on wind-induced responses. The results indicated that podiums significantly reduce displacement, acceleration, inter-storey shear force, and overturning moment, particularly in the lower and middle floors of the main tower. However, podium layout played a critical role: symmetrical podium arrangements yielded smoother displacement profiles, whereas asymmetric configurations caused abrupt response variations at the podium–tower interface. The study concluded that podium geometry is a key aerodynamic and structural parameter and must be optimised to enhance wind vibration control and serviceability performance.

2.4 Comprehensive Review of Wind and Earthquake Vibrations in Skyscrapers

Kousar and Alam (2025) provided a broad review of vibration challenges in skyscrapers arising from wind and seismic actions. The review highlighted how increased building height, slenderness, architectural complexity, and multifunctional usage exacerbate dynamic vulnerability. Fundamental vibration mechanisms such as vortex shedding, buffeting, flutter, galloping, and seismic-induced oscillations were systematically discussed. A notable contribution of this review is the integration of economic considerations, emphasizing that inadequate vibration control can significantly increase life-cycle maintenance costs and risk catastrophic failures. The authors also reviewed advanced mitigation strategies, including tuned mass dampers, base isolation, semi-active and active control systems, aerodynamic optimisation, and AI-based predictive maintenance tools. The study emphasized that sustainable skyscraper design requires a holistic, performance-based approach integrating structural, technological, and economic factors.

2.5 Coupled Wind and Pedestrian Load Effects on Large-Span Structures

Yang et al. (2024) investigated the vibration suitability of large-span double-connected structures subjected to simultaneous wind and pedestrian loading. Using a detailed finite element model developed in ANSYS, the study incorporated pedestrian excitation through Fourier-based models and wind loads via Davenport spectrum-based harmonic superposition. The findings showed that vertical comfort criteria were satisfied when pedestrian density remained below 0.3 persons/m², whereas higher densities led to excessive vibration amplification. Horizontal vibration performance was generally acceptable except under a 0° wind angle, which produced the most unfavourable aerodynamic response. The study demonstrated that the interaction of periodic pedestrian forces with stochastic wind loads significantly increases resonance risk, highlighting the need for combined-load vibration assessment in modern lightweight structures.

2.6 Wind–Rain Coupled Dynamic Response and Vibration Control of Towers

Li and Cheng (2024) examined the dynamic response of a television tower subjected to coupled wind–rain excitation, a loading condition often neglected in conventional design. Numerical simulations revealed that wind–rain interaction produces substantially higher displacements and stresses compared to wind-only loading. Under extreme conditions (wind speed of 40 m/s), structural components exceeded yield limits, indicating potential plastic deformation. The study further evaluated tuned mass dampers (TMDs) and found that a mass ratio of 1.5% and a frequency ratio of 0.9 provided optimal vibration suppression. The authors concluded that rainfall effects must be incorporated into wind-resistant design of slender towers and that TMDs are highly effective in mitigating extreme dynamic responses.

2.7 Wind-Induced Vibrations of Cruise Ship Deck Structures

Feng et al. (2023) investigated wind-induced vibrations of frame structures on open decks of large cruise ships using wind tunnel testing and CFD-based subdomain modelling. The SST $k-\omega$ turbulence model showed excellent agreement with experimental data. The study identified vibration frequencies ranging from 0.8 to 10.1 Hz, indicating potential resonance risks. Critical vibration responses occurred at wind attack angles of 0° and 120°, where aerodynamic excitation was strongest. The results demonstrated that full-ship CFD modelling significantly improves prediction accuracy, while simplified isolated models may underestimate vibration severity.

2.8 Fundamental Mechanisms and Countermeasures for Wind-Induced Vibrations

Ke (2021) provided a fundamental overview of wind-induced vibration mechanisms in high-rise buildings, identifying buffeting, vortex shedding, and self-excited vibrations as primary causes. The study discussed structural optimisation, aerodynamic modification, and damping devices as key mitigation strategies. The author emphasized that aerodynamic shaping during early design stages is the most cost-effective vibration mitigation technique, reducing reliance on supplemental damping systems. The study reinforced that vibration serviceability is equally critical as structural safety in performance-based tall building design.

2.9 Review of Vibration Control Devices and Applications

Kavyashree et al. (2021) reviewed vibration control strategies for tall buildings, categorising them into passive, active, semi-active, and hybrid systems. Passive devices were noted for reliability and low maintenance, while active and hybrid systems offer superior adaptability. The review also highlighted emerging trends such as stochastic vibration control, smart monitoring systems, and data-driven control strategies, indicating a shift toward intelligent and adaptive vibration mitigation frameworks.

2.10 Wind-Induced Vibrations in Traditional Timber Buildings

Han et al. (2021) studied wind-induced vibrations of early Chinese hall-style timber buildings using CFD-coupled FEM analysis. Results showed that wind vibration coefficients derived from time-series analysis were 1.39–1.82 times higher than code-prescribed values, indicating underestimation by simplified design approaches. The study emphasized that low lateral stiffness and dominant low-frequency modes make such structures highly vulnerable to wind excitation, highlighting the need for advanced simulation techniques in heritage conservation.

2.11 Review of Wind-Induced Load Quantification Methods

Hou and Jafari (2020) reviewed wind load and response assessment methodologies, including wind tunnel testing, numerical simulation, and full-scale monitoring. The authors concluded that a combined approach offers the most realistic understanding of wind–structure interaction and supports performance-based design of tall buildings.

2.12 Vibration-Based Structural Monitoring

Fujino (2018) highlighted the importance of long-term vibration monitoring in flexible structures. Case studies demonstrated that real-world monitoring often reveals unexpected vibration phenomena not predicted during design, reinforcing the need for feedback-based design improvements.

2.13 Wind-Induced Vibrations in Tall Buildings and Wind Turbines

Elbakheit (2018) emphasized the catastrophic potential of wind-induced vibrations and identified aerodynamic optimisation as the most economical and effective mitigation strategy for tall buildings and wind turbines.

2.14 Aerodynamic Tapering for Vibration Reduction

You et al. (2007) experimentally demonstrated that tapered building geometries significantly reduce across-wind vibration by disrupting vortex shedding synchronization. Higher taper ratios were found to be particularly effective, validating tapering as a sustainable and cost-efficient vibration mitigation strategy.

III. RESEARCH GAP

Based on the comprehensive literature review, the following research gaps are identified:

1. Limited integration of human cognitive performance metrics into wind vibration design criteria.
2. Insufficient full-scale validation of numerical and CFD-based wind vibration models.
3. Lack of unified serviceability limits applicable to modern lightweight and timber buildings.
4. Inadequate consideration of coupled wind effects with rain, pedestrian loads, and thermal actions.
5. Scarcity of long-term monitoring data linking vibration exposure to occupant health and productivity.
6. Limited optimization frameworks combining aerodynamic shaping and structural control devices.
7. Need for standardized performance-based guidelines incorporating economic and sustainability aspects.

Addressing these gaps will significantly enhance the reliability and resilience of future building designs.

CONCLUSION

This review paper has presented an in-depth evaluation of wind-induced vibrations in building structures, highlighting their causes, effects, and mitigation strategies. The literature confirms that wind-induced vibrations are not merely a comfort issue but a critical performance concern influencing structural serviceability, occupant well-being, and economic sustainability. Modern tall and lightweight buildings demand an integrated design approach that combines aerodynamic optimization, advanced structural analysis, vibration control technologies, and human-centric performance criteria. Traditional code-based methods, while essential, are insufficient to address the complexities of wind–structure–human interaction. Future research should prioritize performance-based design frameworks supported by experimental validation, full-scale monitoring, and intelligent control systems. Such advancements will ensure the development of safe, comfortable, and resilient built environments capable of meeting the demands of rapidly evolving urban landscapes.

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