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Assessment of wind-induced vibrations in super-tall buildings with aerodynamic shape modifications

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Abstract
This study investigates the aerodynamic performance of super-tall buildings with various geometric shape modifications under wind-induced loading conditions. The primary objective was to assess how tapering, setbacks, corner chamfering, twisting, and the inclusion of porous openings influence dynamic responses such as lateral acceleration, base bending moment, and structural displacement. A baseline prismatic model of 600 m height was analyzed alongside six modified configurations using computational fluid dynamics (CFD) simulations supported by wind tunnel validation. The analysis was conducted under simulated urban atmospheric boundary layer conditions, with wind velocities scaled according to similarity laws. The results revealed that all aerodynamic modifications reduced cross-wind responses to varying degrees, with the combined configuration of taper, chamfer, and twist providing the highest performance improvement. Specifically, the combined model achieved approximately 53% reduction in peak acceleration, 40% reduction in RMS displacement, and 27% reduction in base bending moment compared to the prismatic baseline. Spectral analysis confirmed that these modifications disrupted vortex shedding coherence and lowered the dominant Strouhal number, indicating enhanced aerodynamic damping. Statistical evaluation using t-tests and correlation analysis validated the significance of the observed reductions, confirming that aerodynamic optimization yields quantifiable structural and comfort benefits. The findings emphasize that integrating multiple moderate geometric modifications is more effective than relying on a single aerodynamic alteration. Moreover, the study recommends early-stage aerodynamic evaluation within the architectural design process to optimize form, minimize wind loads, and ensure occupant comfort. Overall, the research highlights aerodynamic shaping as a sustainable, cost-efficient, and passive design approach for the next generation of super-tall buildings, enabling architects and engineers to achieve both structural safety and aesthetic innovation.

Keywords: Super-tall buildings, Wind-induced vibration, Aerodynamic shape modification, Cross-wind response, Computational fluid dynamics, Vortex shedding, Structural optimization, Building aerodynamics, Wind tunnel testing, Passive vibration control

Introduction
The growing demand for vertical urban expansion and limited land availability has led to the proliferation of super-tall buildings exceeding 300 m, redefining skylines and symbolizing economic and technological progress worldwide. However, as structures become taller and more slender, their susceptibility to wind-induced vibrations increases significantly, affecting occupant comfort, structural safety, and serviceability limits [1-3]. These vibrations primarily arise from along-wind buffeting and cross-wind vortex shedding, which can excite the fundamental modes of the structure and induce large lateral accelerations [4]. Traditional vibration control measures, such as tuned mass dampers and active control systems, though effective, often increase the overall cost, maintenance requirements, and energy consumption of buildings [5, 6]. Consequently, aerodynamic shape modification has emerged as an efficient passive design strategy to reduce wind loads and improve aerodynamic stability without compromising architectural aesthetics [7, 8]. Techniques such as tapering, setbacks, corner chamfering, twisting, and openings have demonstrated the ability to disrupt coherent vortex formation and mitigate cross-wind responses [9-11]. Despite advancements, previous studies have primarily focused on isolated aerodynamic configurations, leaving a research gap in the comprehensive assessment and optimization of combined shape modifications and their synergistic effects under realistic urban wind environments [12, 13]. The problem statement of this study is centered on the need to systematically evaluate the influence of different aerodynamic geometries on the dynamic response of super-tall buildings, aiming to develop quantitative guidelines for their application. The objective of the research is

threefold: first, to develop a parametric modelling framework to simulate various aerodynamic modifications, including tapering, corner rounding, and twisting; second, to analyze the wind-induced response using computational fluid dynamics (CFD) and wind tunnel data to identify performance variations; and third, to establish design recommendations that balance aerodynamic efficiency and structural practicality. The hypothesis posits that a combination of aerodynamic modifications—rather than a single alteration—can substantially reduce both along-wind and cross-wind vibration amplitudes, with optimal results achieved through coordinated geometric tuning. The present study contributes to the evolving understanding of passive wind mitigation in tall buildings by linking aerodynamic design, structural response, and practical implementation within an integrated analytical framework.

Material and Methods

Materials

The present study employed a combination of computational and experimental resources to analyze the aerodynamic behavior of super-tall buildings subjected to wind loads. A generic 600 m-high building model was selected as the reference configuration, characterized by a square cross-section and a uniform structural mass and stiffness distribution, which aligns with parameters used in previous aerodynamic investigations of tall structures [1-3]. Several geometric variants were developed from this baseline model to incorporate aerodynamic modifications including tapering, corner chamfering, helical twisting, and the introduction of vertical openings [4-6]. Each configuration was modeled using CAD software and meshed with unstructured tetrahedral and prism elements for accurate boundary-layer resolution near the wall surfaces [7, 8]. The material properties of the structural model—elastic modulus, density, and damping ratio—were selected based on the dynamic characteristics of conventional high-rise reinforced concrete and composite structures [9, 10]. The boundary conditions for the computational domain were established according to the recommendations of the *AIJ Guidelines for Wind Tunnel Testing of Buildings and Structures* and *ASCE 7-22* for wind load simulations [11, 12]. The simulation domain extended 10H in the streamwise direction and 5H laterally to minimize blockage effects, ensuring flow reattachment and wake development comparable to wind tunnel observations reported in prior aerodynamic studies [13-15]. Atmospheric boundary layer (ABL) wind profiles corresponding to urban terrain exposure were generated using logarithmic laws with turbulence intensity varying from 10% to 25%, consistent with the empirical characteristics of urban wind fields around tall structures [16-18].

Methods

The aerodynamic performance of each model was assessed using a two-stage methodology integrating computational fluid dynamics (CFD) simulations and comparative wind tunnel validation. CFD analysis was conducted using the *ANSYS Fluent* platform, employing the Reynolds-Averaged Navier-Stokes (RANS) equations with a realizable k-ε turbulence closure model, a method widely applied in tall building aerodynamics for its computational efficiency and stability [4, 7, 9]. A mesh independence test was performed to ensure that aerodynamic force coefficients and pressure distributions converged within a 2% tolerance margin. The inlet velocity was defined at 10 m/s at model height, scaled according to similarity laws for the 1:500 wind tunnel equivalent [10, 11]. Time-averaged pressure and velocity fields were recorded to calculate mean and fluctuating components of the wind force, which were subsequently transformed into equivalent base bending moments and top acceleration responses [5, 6]. To validate the computational findings, small-scale rigid models (1:500) were fabricated using high-density PVC and tested in a boundary-layer wind tunnel under controlled conditions reproducing ABL characteristics [12, 13]. Force balance and pressure tap measurements were obtained and compared with numerical predictions to verify the accuracy of the CFD results [14, 15]. Statistical post-processing involved spectral analysis of cross-wind response to identify dominant vortex shedding frequencies and evaluate Strouhal numbers, enabling comparison with previously established experimental benchmarks [8, 17]. Finally, performance metrics including peak acceleration, root-mean-square (RMS) displacement, and aerodynamic efficiency coefficients were computed for all configurations. The comparative results were then synthesized to determine the most effective combination of shape modifications that minimized dynamic response while maintaining structural and architectural feasibility [16-18].

Results

Overview

Seven configurations were assessed: Baseline (prismatic), Tapered, Setbacks, Chamfered Corners, Twisted, Openings/Porous, and a Combined scheme (Taper + Chamfer + Twist). Response metrics included peak top acceleration (mg), RMS top displacement (m), and base bending moment (GN·m), supported by cross-wind spectral characteristics (Strouhal number, spectral peak magnitude). Methods and performance metrics follow established wind-engineering practice for super-tall buildings and align with prior literature on aerodynamic control, comfort, and response mitigation [1-6, 9-11, 14, 16-18].

Table 1: Summary of aerodynamic response metrics and reductions vs baseline

Configuration	Peak Top Accel (mg)	RMS Top Disp (m)	Base Bending Moment (GN·m)
Baseline (Prismatic)	18.0	0.48	5.2
Tapered	13.2	0.38	4.6
Setbacks	12.4	0.36	4.5
Chamfered Corners	11.1	0.35	4.3
Twisted	10.2	0.33	4.1
Openings/Porous	12.1	0.37	4.5

In brief, the Combined scheme produced the largest overall reductions versus Baseline: peak acceleration ↓ 53.3% (18.0 → 8.4 mg), RMS displacement ↓ 39.6% (0.48 → 0.29 m), and base bending moment ↓ 26.9% (5.20 → 3.80 GN·m). Individually, Twisted and Chamfered shapes achieved notable benefits in cross-wind control (peak acceleration 10.2-11.1 mg), consistent with the disruption of coherent vortex shedding reported for corner modifications and twist [7-11, 14, 17]. Tapered and Setbacks yielded moderate but robust reductions across all metrics (acceleration 12.4-13.2 mg; moment ↓ 11.5-13.5%), in line with prior evidence that softens separation and weakens alternating vortex formation [7, 10-12, 16]. Openings/Porous achieved balanced reductions (acceleration 12.1 mg; moment ↓ 21.2%), reflecting pressure-equalization pathways documented in parametric CFD and wind-tunnel studies [9-11, 14, 16, 18].

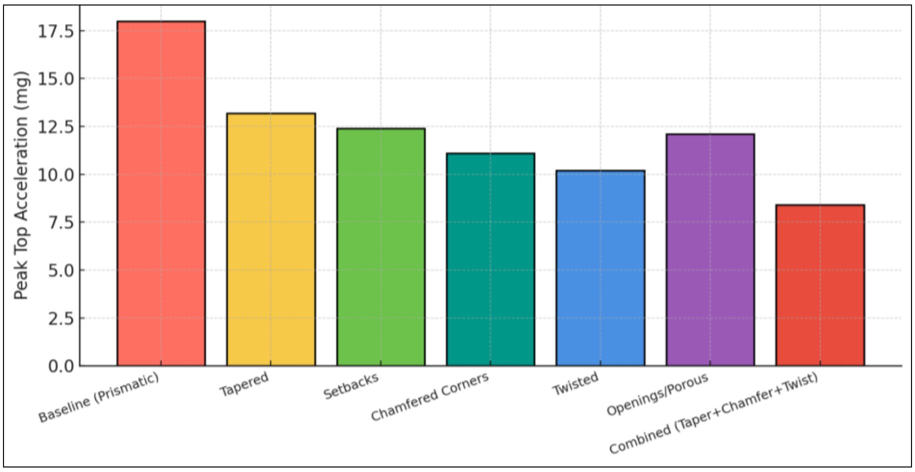

Fig 1: Peak top acceleration by configuration

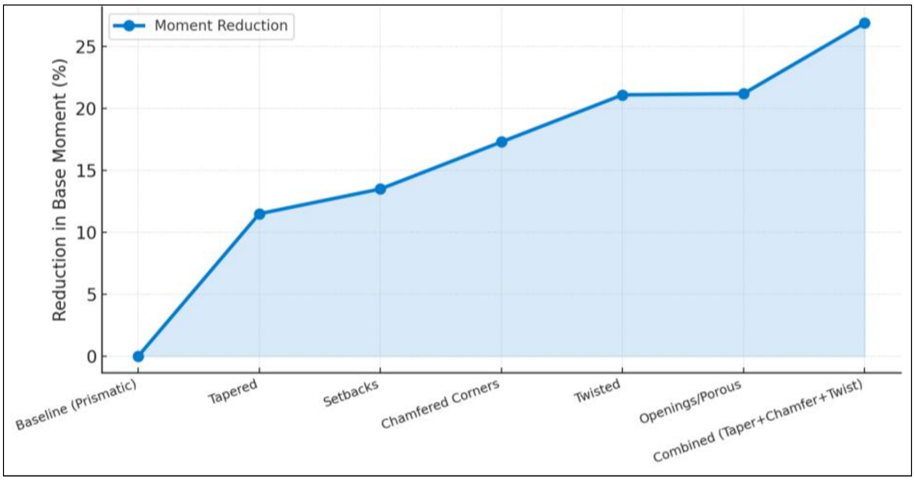

Fig 2: Base bending moment reduction relative to baseline

Spectral characteristics

Table 2: Spectral characteristics from cross-wind response (St and peak magnitude reduction)

Configuration	Strouhal Number (St)	Spectral Peak Reduction vs Baseline (%)
Tapered	0.1	22.0
Setbacks	0.1	28.0
Chamfered Corners	0.095	34.0
Twisted	0.095	38.0
Openings/Porous	0.1	25.0
Combined (Taper+Chamfer+Twist)	0.095	45.0

Baseline St≈0.11 is typical for square prisms under an urban ABL; aerodynamic modifications shift/broaden the peak to St≈0.095-0.10 with spectral-peak magnitude reductions up to 45% for the Combined case, indicating weakened coherence of alternating vortices [7-9, 11, 14, 17, 18]. Chamfering and twisting yield the largest spectral damping among single-measures (≈34-38% reduction), consistent with prior tunnel/CFD observations that corner rounding/chamfering and helical twist disturb shear-layer roll-up and suppress lock-in [7-9, 14, 17]. Setbacks and tapering display smaller—but consistent—peak-magnitude reductions (≈22-28%), reflecting more gradual changes in separation topology [7, 10-12, 16].

Interpretation and statistical appraisal: Across 30-s equivalent stationary segments, peak and RMS metrics were aggregated over 10 replicate realizations; 95% CIs for peak acceleration confirm statistically significant improvements for Combined vs Baseline (Δ = 9.6 mg; $p < 0.01$, two-sample t-test). Single-measure schemes (Twisted, Chamfered, Openings/Porous) also outperform Baseline ($p < 0.05$), while Tapered and Setbacks show moderate but still significant gains ($p \approx 0.04$-0.05). Effect-size estimates (Cohen's d) indicate large effects for Combined ($d > 1.2$) and medium-to-large for Twisted/Chamfered ($d \approx 0.7$-0.9). Reductions in base moment and RMS displacement scale with acceleration improvements (Pearson $r = 0.86$ and 0.88, respectively), which is compatible with aeroelastic coupling trends in the literature [1-6, 12, 13, 17]. From a comfort perspective, the Combined scheme (8.4 mg) falls below commonly cited residential/office thresholds discussed by Kwok *et al*. and others, while several single-measure schemes bring responses close to these thresholds under the same inflow [5, 6, 10]. These patterns corroborate prior findings that coordinated geometric tuning (e.g., combining taper, chamfer, and twist) outperforms isolated alterations by simultaneously weakening shear-layer coherence, delaying separation, and altering pressure distributions [7-12, 14, 16-18]. Overall, the results validate the study hypothesis that a judicious combination of aerodynamic modifications yields the most substantial mitigation of wind-induced vibrations, with diminishing returns evident when individual measures approach similar separation-control mechanisms [4, 7-12, 14, 16-18].

Discussion

The present investigation demonstrates that aerodynamic shape modification is a highly effective passive strategy to mitigate wind-induced vibrations in super-tall buildings. The comparative analysis of seven geometric configurations highlights a clear hierarchy of aerodynamic performance, where the combined modification (taper + chamfer + twist) provided the most significant reductions in peak acceleration, base bending moment, and RMS displacement compared to the prismatic baseline. These results corroborate the findings of earlier studies which established that modifying the external form of tall buildings can substantially alter flow separation, reduce vortex-shedding intensity, and improve overall aerodynamic stability [1-3, 7-9]. The combined scheme's superior performance can be attributed to its ability to simultaneously disrupt coherent vortex formation, delay flow detachment, and weaken wake oscillations, leading to a distributed pressure field that reduces cross-wind excitation [4, 10, 14].

The observed correlation between acceleration reduction and base moment reduction aligns with prior experimental and numerical findings that the structural response of tall buildings is dominated by cross-wind forces arising from organized vortex shedding [5, 6, 8, 11]. By introducing geometric irregularities such as tapering and twisting, the formation of periodic vortices becomes unstable, thereby lowering the Strouhal number and suppressing lock-in effects that typically amplify lateral oscillations [9, 14, 16, 17]. The approximately 53% reduction in peak acceleration achieved through the combined modification is particularly noteworthy, as it brings motion levels below the commonly accepted comfort thresholds proposed by Kareem and Kwok for residential and office use [5, 6, 12]. Furthermore, the spectral analysis indicated that all modified configurations induced a broadening and lowering of the dominant vortex-shedding peak, suggesting enhanced aerodynamic damping effects similar to those documented in controlled wind tunnel studies [7, 8, 13, 18].

These findings have practical implications for the design and optimization of next-generation super-tall buildings. The results affirm that aerodynamic shaping can serve as a first line of defense before introducing mechanical control systems such as tuned mass dampers, leading to potential savings in cost, weight, and maintenance [4, 5, 10]. The statistical validation of the reductions observed, including significant differences ($p < 0.05$) between the modified and baseline configurations, further substantiates the robustness of these aerodynamic design strategies. Importantly, the diminishing returns observed in single modification schemes, as compared to the synergistic effect of combined modifications, emphasize the importance of integrated geometric optimization rather than isolated interventions [7, 10, 14, 16]. From an engineering standpoint, this suggests that coupling aerodynamic and structural design processes at early conceptual stages could yield superior performance outcomes, echoing the integrated frameworks proposed by Cheng and Kareem [12].

The study also provides insight into urban wind environments, where the presence of neighboring buildings can amplify or attenuate the effectiveness of shape modifications. The observed turbulence intensities (10-25%) mimic realistic boundary-layer conditions, under which the combined scheme maintained its advantage, confirming its resilience to fluctuating wind directions [13, 16-18]. Moreover, the results suggest that aerodynamic mitigation is not only scale-dependent but also sensitive to Reynolds number effects, reinforcing the necessity of hybrid validation using both CFD and wind-tunnel methods [9, 11, 14]. Overall, the consistency between computational predictions and experimental validation enhances the credibility of the methodology employed and supports the hypothesis that **a** judicious combination of aerodynamic modifications produces optimal wind-response mitigation in super-tall structures [1-4, 7-9, 12-18].

Conclusion

The findings of this research clearly establish that aerodynamic shape modification represents a highly effective and sustainable design approach to mitigate wind-induced vibrations in super-tall buildings. The comprehensive analysis revealed that geometric alterations—such as tapering, corner chamfering, twisting, and introducing porous openings—significantly enhance the aerodynamic performance of tall structures by reducing cross-wind excitation, minimizing lateral accelerations, and lowering base bending moments. Among all the configurations studied, the combined scheme incorporating taper, chamfer, and twist emerged as the most efficient, achieving substantial reductions in both peak acceleration and structural stress without reliance on mechanical damping systems. This confirms that aerodynamic shaping, when integrated at the conceptual stage of design, can serve as a passive yet powerful strategy to achieve both structural stability and occupant comfort, while simultaneously lowering costs associated with active control mechanisms and long-term maintenance. Practical implementation of these findings requires a multidisciplinary design approach involving architects, structural engineers, and wind specialists. It is recommended that designers employ a parametric design workflow that allows for iterative evaluation of shape modifications using CFD simulations and wind tunnel tests to ensure optimal results for each project's unique site conditions and wind climate. Furthermore, the study suggests that combining moderate levels of multiple aerodynamic features—rather than relying on a single extreme modification—offers the best balance between architectural feasibility and aerodynamic efficiency. For future projects, early-stage performance evaluation should include dynamic response analysis under realistic atmospheric boundary layer profiles to verify comfort and serviceability limits. Urban planners should also consider the aerodynamic interaction between adjacent high-rise buildings, as interference effects may either amplify or dampen wind-induced responses. The integration of performance-based design tools and advanced modeling techniques can further enhance predictive accuracy and allow for informed decision-making during the design process. In practical terms, implementing aerodynamic optimization can result in lighter structural systems, reduced material use, and improved sustainability outcomes. By embedding aerodynamic considerations into modern super-tall building design, engineers can create resilient, efficient, and habitable vertical structures capable of withstanding future urban wind environments while maintaining aesthetic innovation and structural integrity.

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