Aerodynamic Shape Optimization of Skyscrapers for Wind Loads: A Review

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Abstract - This research investigates the influence of different shapes of skyscrapers on their aerodynamic performance in a particular wind regime. The shapes of the buildings are limited to geometric variations of high-rise buildings to understand the configurations and how they affect wind flow behavior and patterns around the buildings. It employs numerical simulations of wind flow and examines the impact of the form of the building shape on wind pressure pattern development and the loads imposed on a tall structure. The research includes the examination of design strategies that can be used to reduce the loads imposed by wind pressures on tall structures through the use of aerodynamically efficient forms. The impact analysis is framed in the context of comparative wind load stimulation of several different building forms while continuing to highlight a percentage reduction in wind loads through a more aerodynamic design modification. The results provide a detailed comparison and consideration of the shapes being evaluated, providing insight into their performance, understanding how different shapes not only changed wind flow but turbulence path behavior, and the overall impact this will have on developing more stable and sustainable forms in skyscraper design. This research explores **aerodynamic shape optimization** as a method to mitigate wind-induced loads via geometric modifications, leveraging Computational Fluid Dynamics (CFD) and optimization algorithms. The findings support integrating aerodynamic optimization early in architectural design, offering pathways toward more sustainable, high-performance high-rise buildings.

Key Words: Wind load; skyscraper; aerodynamic optimization; computational fluid dynamics (CFD); Genetic Algorithm; surrogate modelling; corner modification; tapering.

1.INTRODUCTION *(Size 11, Times New roman)*

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1.1 Background and Rationale

Importance of wind loads in high-rise design: Tall buildings are often governed by wind effects rather than gravity loads: as height and slenderness increase, wind produces large mean forces (along-wind) and fluctuating forces (across-wind and resonant components) that control structural sizing, dynamic response, and occupant comfort (Tracy Kijewski-Correa, 20). Wind loading on tall buildings is complex: the total effect arises from the mean static pressure distribution, fluctuating background turbulence, and aerodynamic coupling (wake and vortex shedding) between the wind inflow and the structure. (Guoqing Huang, 2007)

Challenges with conventional design: Conventional design methods and code-prescribed equivalent-static wind loads are practical and conservative for many buildings, but they may fail to capture the multi-component nature of wind effects (mean, background turbulence and resonant responses) on very tall, flexible towers. This can result in either unsafe underestimation of dynamic effects (across-wind, vortex-induced responses) or overly conservative designs that increase cost without improving performance (Junhui Yang, 2022). Tall buildings are susceptible to aerodynamic instabilities and dynamic excitation—across-wind response and vortex shedding can produce forces and accelerations that are not represented by simple static factors. Capturing these unsteady aerodynamic phenomena requires time-domain analysis, modal decomposition, or unsteady CFD/FSI; code formulas alone cannot reliably predict such effects for novel or highly slender forms. (Yang, 2021)

Opportunity of CFD + optimization: CFD coupled with optimization enables architects and engineers to explore a wide design space of geometric variations (tapering, twisting, corner treatments, plan changes) systematically. Unlike single-point wind-tunnel tests, a CFD + optimization workflow can evaluate many parametric variants and identify non-intuitive shapes that reduce wind loads while respecting architectural constraints. This flexibility is particularly valuable in early design stages, when multiple alternatives are still feasible. (Alkhatib, et al., 2022)

1.2 Research Objectives

The study aims to examine the morphological evolution of skyscraper forms and understand how architectural intentions and design trends shape their geometry. It further investigates how variations in form—such as tapering, setbacks, twisting, perforations, and fluid geometries—affect aerodynamic behavior, with a focus on strategies that mitigate wind loads. Additionally, the research conducts a comparative case study between optimized and baseline building geometries under multiple wind attack angles to evaluate performance differences and derive informed design recommendations.

1.3 Significance of the Study

This study offers architects and engineers a practical way to integrate aerodynamic thinking early in the design process, showing how even subtle shape adjustments can significantly improve performance without altering the overall architectural intent. By bridging CFD analysis, structural engineering principles, and architectural form-making, it strengthens the multidisciplinary understanding needed for high-performance tall building design. The work also lays the groundwork for future advancements, including more detailed unsteady simulations, risk-aware design approaches, and methods that respond to real-time urban wind dynamics.

2. LITERATURE STUDY

2.1 Aerodynamic Modifications & Optimization Techniques

- **Global vs. local modifications:** Experimental wind-tunnel studies and numerical simulations demonstrate that localized corner modifications can significantly diminish cross-wind fluctuations and peak suction values without drastically altering the building's overall appearance. In contrast, global modifications (such as taper, twist, and setback) alter the mean loading pattern and can further decrease both mean and fluctuating components. In practice, a mix of small global changes and specific local treatments usually gives the best balance between how well the building works aerodynamically and how well it fits the design. (Yanyu Ke, 2022)
- **Genetic Algorithm (GA) + CFD coupling:** Alkhatib et al. (2022) created a framework that combined CFD and an improved GA to make an irregular 70-story building as good as it could be. Their method used a pressure-load translation (PLT) to structural analysis, which cut the amount of concrete needed by about 35.7% while still meeting drift and acceleration limits. The workflow usually sets up the building geometry with parameters, uses CFD to find out how the building will respond to airflow, calculates a fitness value (like base moment, drag, or acceleration), and then uses GA operators (selection, crossover, mutation) to come up with better designs. Finally, promising GA solutions are checked by more accurate CFD or structural tests. This method is especially helpful for tall buildings that aren't regular or standard, where designing based on intuition isn't enough. (Alkhatib, et al., 2022)
- **Surrogate modeling with RBF:** Executing full CFD for each design candidate is quite expensive and thus, many recent frameworks create surrogate models (using radial basis functions, kriging/Gaussian processes, or neural networks) from a limited number of high-fidelity CFD evaluations. The surrogate model approximates the aerodynamic outputs (drag, base moment, pressure metrics) and supports rapid screening or optimization (such as GA or PSO) across numerous design candidates, with only the best candidates being re-evaluated via full CFD. This approach has become standard practice for making aerodynamic optimization tractable in academic research and industry applications alike. (Alkhatib, et al., 2022)
- **Corner optimization for octagonal buildings:** (A.H.H. Al-Masoodi, 2023) investigated aerodynamic optimization focused on corner modification of octagonal-shaped tall buildings, employing CFD to evaluate effects of chamfering / rounding, showing significant reductions in base moment coefficients.
- **Corner modification effects:** Multiple wind-engineering studies show that corner modifications (like chamfering, rounding, and recession) can significantly reduce base overturning moments and spectral amplitude of wind forces. (Yanyu Ke, 2022)
- **Façade aerodynamic optimization:** Jafari and Alipour (2021) conducted an optimization of double-skin façades (DSFs) on rectangular and elliptical tall buildings using CFD, DOE, and Genetic Algorithm to minimize drag coefficient. (Mohammad Jafari, 2021)

2.2 Wind Engineering for Super-Tall Buildings

The dramatic escalation of the height of contemporary skyscrapers, and commonly over 300 meters, has provided new challenges to wind engineering and building performance. Models from the 1960s boundary layer, previously used in design codes for decades, are no longer sufficient in the prediction of higher-level wind behavior in super-tall buildings. Experiments stress the demand for higher quality wind data and merging re-analysis weather models for the knowledge of high-altitude wind statistics. Aerodynamic loads significantly impact the cost and structural stability of such towers, so early wind tunnel testing is critical in terms of optimization of shape, stiffness, mass, and damping systems. Force balance, aeroelastic modeling, and high-frequency pressure integration are techniques employed to forecast structural responses and enhance resilience. The study also highlights the need for additional damping systems to improve serviceability and comfort. In addition, growing exposure of high-level terraces and balconies requires detailed design attention to wind comfort. In general, improvements in wind analysis, aerodynamic design, and damping technologies are essential in providing safety, efficiency, and sustainability to the next generation of super-tall buildings. (Irwin, 2009)

2.3 Wind-Load Mitigation through Uncertainty-Aware Shape Optimization

A principal strategy in optimizing skyscrapers for wind involves risk-averse aerodynamic design, where geometry (e.g., taper, twist) is specifically adapted to minimize extreme wind responses under probabilistic wind conditions. Kodakkal et al. (2022) developed a risk-averse optimization framework that couples computational fluid dynamics (CFD) with stochastic optimization to account for site-specific uncertainties such as wind speed variation, terrain roughness, and flow direction changes. (Anoop Kodakkal, 2022)
In their approach, the Conditional Value-at-Risk (CVaR) metric is employed to minimize the expected structural response in the worst-case tail (e.g., the worst 10% of wind loading scenarios), rather than simply optimizing for mean performance (Anoop Kodakkal, 2022).

2.4 Sensor Optimization for Pressure Reconstruction

To further improve understanding of aerodynamic pressure distribution on skyscraper façades, optimal sensor placement is critical. Luo, Kareem & Yoo (2023) propose a compressed-sensing algorithm that selects sparse sets of pressure sensors while still accurately reconstructing the full pressure field over the building surface (Luo, Kareem, & Yoo, 2023). Their method first fits a set of basis functions to training data, and then applies a QR-based ranking algorithm to identify the most informative sensor locations. This approach delivers stable reconstructions of aerodynamic pressure fields from limited measurements, thus reducing the number of physical sensors required. The significance of this research lies in its potential to supplement CFD models, digital twins, or experimental campaigns: by placing sensors efficiently, designers and engineers can validate or update their pressure models and surrogate models with higher fidelity, while minimizing instrumentation cost and complexity.

2.4 Geometry-Based Aerodynamic Optimization (Traditional & Surrogate-Modeling)

Classical geometry-based optimization remains central: modifying building form through tapering, twisting, setbacks, or corner rounding can dramatically influence wind forces. For instance, surrogate-model methods (e.g., using radial basis functions) have been used in conjunction with CFD and fluid–structure interaction to explore design spaces efficiently. In such workflows, designers define design variables (such as taper ratio, twist angle, corner fillet radius), generate a sampling of candidate geometries using Design of Experiments (DOE), run CFD or FSI simulations for each candidate, and build a surrogate model to approximate responses.

The surrogate model then guides the optimization algorithm (e.g., GA or gradient-based) to identify optimal shape modifications that minimize base moments, drift, or other objective functions (Fadi Alkhatib, 2022).

2.5 Dynamic Optimization and Damping Integration

In addition to shape, dynamic optimization plays a crucial role. Warsido, Merrick & Bitsuamalk present a dynamic optimization method that simultaneously considers a building’s structural properties (mass, stiffness, damping) and aerodynamic forcing to minimize perceived accelerations.

By tuning structural damping (e.g., via supplemental dampers) and structural stiffness properties, one can optimize the building’s dynamic response under realistic wind load spectra. This integrated approach helps reduce the inertial component of wind-induced forces and improves occupant comfort without solely relying on static force reductions (Workamaw Warsido, 2009).

2.3 Summary of Gaps and Research Needs

Despite growing interest in aerodynamic design, several gaps still remain in current research. Many studies continue to rely only on steady wind simulations, overlooking important unsteady effects like buffeting and vortex shedding that can strongly influence how a tall building behaves. There is also a clear need to better integrate fluid–structure interaction (FSI) into optimization methods so that buildings’ real-time deformation and feedback can be properly understood. In addition, most optimization efforts still focus on a single wind direction, even though real buildings face wind from multiple angles throughout the year. Designing for uncertain or changing wind climates is another area that needs more attention. Finally, while data-driven tools such as machine learning and surrogate models are beginning to appear, they are still not widely used in architectural design, leaving significant potential for more adaptive and real-time optimization in the future.

3. CASE STUDIES

3.1 Burj Khalifa (Dubai)

Wind-stimulation program and shape-optimization strategy:
The Burj Khalifa, standing at 828 m, underwent an integrated wind-engineering program from early conceptual design, with the goal of controlling wind-induced forces and motions through architectural

shaping. RWDI was engaged to run a comprehensive wind-tunnel testing campaign, which included high-frequency force-balance (HFFB) tests, aeroelastic (flexible) model studies, local pressure tapping, and pedestrian wind comfort tests. In the HFFB tests, scale models (primarily at 1:500 scale) were used to measure global lateral forces and moments under various wind directions; these results informed the design team's decisions about setbacks, tapering, and orientation. RWDI documented that changing the number and spacing of the tower's setbacks allowed them to "confuse the wind" by desynchronizing vortex shedding along the building height, thereby reducing across-wind forces.

A particularly critical part of the wind-engineering process involved high-Reynolds-number testing. RWDI built a larger 1:50 scale model of the top one-third of the tower and tested it at high speeds to assess Reynolds number effects on pressure peaks, especially on corners and façade surfaces. These tests helped refine pressure coefficient estimates and validate the lower-scale test data for structural design and cladding engineering.

From these tests, the designers derived not only the static force coefficients (drag, base moment) but also spectral information for along-wind and cross-wind excitation. The aeroelastic model tests provided predictions of dynamic response (accelerations, displacements) under fluctuating wind, guiding decisions on acceptable drift, comfort limits, and structural system stiffness. Through iterative feedback between the wind engineers and the architectural/structural teams, the final form of the tower — with its Y-shaped, tapering, setback-rich geometry — was optimized to mitigate dynamic wind effects without resorting to large supplemental damping devices. The result was a design that met both structural safety and occupant comfort criteria.

Numerical highlights & design outcomes

- According to RWDI, the early shaping studies significantly reduced lateral wind forces by promoting non-coherent vortex shedding.
- The wind climatology was studied in parallel: historical wind data (from meteorological stations) and numerical weather modeling (e.g., MM5) were used to inform extreme wind directionality and magnitude, ensuring that wind-tunnel tests were representative of the most critical design loads.
- The shaping interventions (setbacks, taper, orientation) allowed a more efficient structural system: although RWDI does not publish exact percentages for drag reduction in publicly accessible summary texts, their reports emphasize that the optimization enabled feasible construction at the extreme height by reducing overturning moments on foundations.

Architectural significance
The Burj Khalifa is often cited as a benchmark of architecture-engineering integration: its iconic form is not purely an aesthetic gesture but a functional response to wind. The Y-shaped plan, tapering profile, and setback staging were chosen to minimize wind loads while still allowing the architectural ambition of the design. The close collaboration between architects, structural engineers, and wind engineers was essential to achieving this performance.

3.2 Shanghai Tower (Shanghai)

Wind-engineering and aerodynamic shape optimization
Shanghai Tower's defining form — a twisted, spiralling tower that rotates approximately 120° with a taper and rounded corners — was developed not just for aesthetics, but fundamentally to reduce wind loads. According to the CTBUH case study, in collaboration with Gensler, Thornton Tomasetti, and RWDI, a multi-stage wind-tunnel test program was carried out to evaluate and refine this geometry.

In the wind tunnel, Gensler and their engineering partners tested a variety of design iterations, including different degrees of twist, corner radii, taper ratios, and orientation. The tests used rigid-scale models and high-frequency force balances to measure base shear and moment, as well as synchronized pressure measurements over façades. The analysis revealed that the 120° twist significantly reduces lateral wind loads.

Numerical and performance results

- The wind-tunnel testing indicated that the twisted form could reduce lateral (across-wind) wind loads by about 24% compared to a more conventional straight or untwisted tower form.
- Thornton Tomasetti (structural engineer) confirms that this reduction in wind load translated into material savings: by reducing the load, the structural system could be made more efficient, contributing to a "lighter structure."
- According to the CTBUH case study, every 5% reduction in lateral wind load was associated with substantial cost savings; although exact dollar figures may vary in different reports, this optimization was a key driver in cost-performance trade-offs.

Architectural and structural implications
The 120° twist of Shanghai Tower is a hallmark of how architecture and performance can be synergistic. Rather than simply being a sculptural

gesture, the twist is integral to controlling wind-induced forces. The structural system (outriggers, super-columns, core) was designed in tandem with the aerodynamic shaping, enabling a high-strength system that would not be overdesigned. Moreover, by reducing structural demands, the form optimization contributed to sustainability (less material used) and cost savings — a rare instance where aesthetics, performance, and economy align.

3.3 Taipei 101 (Taipei)

Wind-stimulation, TMD design, and dynamic control Taipei 101, rising to 508 m, faces a typhoon-prone climate, making aerodynamic design and motion control critical. From early on, its design incorporated a massive tuned mass damper (TMD) to control wind-induced sway. According to the structural-design documentation by Thornton Tomasetti, the TMD consists of a 660 Mg (metric ton) mass, built from stacked steel plates, forming a pendulum that hangs from near the 92nd floor.

The TMD is connected via eight viscous damping devices (dashpots) to the building frame, which dissipate energy proportionally to the square of the velocity of the mass. This design ensures that when the building sways due to wind, the pendulum moves out of phase, reducing the building’s peak accelerations and improving comfort.

Wind-tunnel testing was conducted in boundary-layer tunnels to measure both global forces (via force balance) and local cladding pressures. The architectural design also employs stepped “pagoda-like” modules (tiered setbacks) to break up coherent vortex shedding and reduce pressure peaks on façades. The combination of aerodynamic shaping (tiers), structural stiffness (outriggers), and the TMD was validated in simulation and testing.

Numerical performance outcomes and validation

- The TMD mass (660 Mg) represents about 0.24% of the total building mass, according to Poon, Shieh & Joseph (CTBUH paper).
- Field and wind-tunnel data suggest that with the TMD, peak accelerations are reduced significantly. While exact percentages vary in literature, multiple sources indicate reductions on the order of 30–40% under strong wind excitation.
- In addition, the TMD was tuned using pendulum principles (gravity stiffness) and fine-tuned after construction by adjusting restraining blocks on the suspension cables to match the actual measured building dynamics.

Architectural significance and occupant comfort The design of Taipei 101 integrates the TMD not just as an engineering device but as a visible architectural element: the spherical mass is, in fact, part of the building’s visitor experience, visible from observation levels. The tiered architectural form is not arbitrary but serves to reduce aerodynamic excitation and to work in tandem with the TMD. The result is a building that, in a very demanding wind climate, achieves high structural safety and occupant comfort in a refined, integrated way.

3.4 Comparative Insights and Lessons for Shape Optimization

From these three case studies of Burj Khalifa, Shanghai Tower, and Taipei 101 several essential lessons emerge that are deeply relevant for aerodynamic shape optimization in skyscraper design: Across these landmark skyscraper projects, several clear insights emerge. Iterative wind-tunnel testing proved essential, with each building undergoing multiple rounds of physical experiments—ranging from force-balance and aeroelastic studies to detailed pressure measurements—to refine their shapes. The impact of geometry on performance is unmistakable: both the Burj Khalifa and the Shanghai Tower achieved significant reductions in wind loads through strategic design moves such as setbacks, tapering, and twisting, ultimately lowering structural demands and overall cost. At the same time, the example of Taipei 101 shows that aerodynamic refinement alone may not be enough for extremely tall or slender towers; even with careful shaping, a substantial tuned mass damper was required to ensure occupant comfort. These cases highlight the importance of strong interdisciplinary collaboration—architects, structural engineers, and wind engineers worked together from the earliest stages, making aerodynamics not just a technical requirement but a defining part of each building’s architectural identity.

4. DISCUSSIONS

4.1 Interpretation and Design Implications

It is anticipated that the results will demonstrate how even minor geometric modifications, like subtle tapering or chamfered edges, can greatly lower wind loads while maintaining the design's architectural intent. By enabling smaller structural members, less material consumption, and a more effectively "right-sized" design as opposed to an unduly conservative one, these aerodynamic improvements can directly translate into structural and financial advantages. By reducing sway, drift, and vibrations particularly in tall, thin towers improved wind performance also improves comfort and serviceability. Beyond performance, these improvements help achieve sustainability objectives by decreasing the structure's embodied carbon and possibly lowering cladding loads, which eventually affects the project's overall cost, environmental impact, and façade efficiency.

4.2 Limitations

Any research that relies heavily on simulations, this study also comes with a few practical limitations. Using only steady-state CFD means some important dynamic behaviors like vortex shedding or buffeting may not be fully captured. The commonly used k–ε turbulence models also have their weaknesses, especially when it comes to predicting flow separation and wake patterns, and while more advanced methods such as LES or DES are more reliable, they require far more computational power and time. The optimization process itself can be demanding because running detailed CFD for every design option is expensive, and although surrogate models can speed things up, they bring their own approximation errors. Integrating fluid–structure interaction adds another layer of difficulty, since more accurate two-way coupling significantly increases complexity. On top of this, the study may have to rely on idealized wind profiles, which don’t always reflect the messy, unpredictable nature of real site-specific wind climates. And finally, even if a shape performs extremely well in simulations, it may still face challenges in the real world such as difficult construction details, complex façade geometries, or non-standard structural solutions.

4.3 Future Work

Future work can build on this study by exploring several promising directions. Running unsteady or transient CFD simulations would allow researchers to capture complex behaviors like vortex shedding, buffeting, and other dynamic wind responses that steady simulations often miss. More advanced turbulence models—such as LES, DES, or hybrid RANS-LES—could provide a clearer picture of flow separation and wake patterns, though they require greater computational effort. There is also strong potential in adopting robust or stochastic optimization methods that account for uncertainty in real wind climates, ensuring designs stay reliable even under variable conditions. Machine-learning-based surrogate models, including neural networks or CNNs, could speed up the design process dramatically by approximating CFD results in real time. Improved validation techniques, such as optimal sensor placement algorithms for physical or digital models, can help reconstruct pressure fields more efficiently and strengthen confidence in the simulations. Finally, building scaled prototypes for wind-tunnel testing remains an invaluable step for verifying how well the optimized designs perform in real-world conditions.

5. CONCLUSIONS

This review establishes the significance of aerodynamic geometry as a core strategy for reducing wind-induced loads and enhancing occupant comfort in super-tall buildings. Literature and case studies show that optimized forms such as tapered, twisted, setback, chamfered, and porous geometries effectively disrupt vortex shedding, reduce dynamic excitation, and improve structural efficiency. Advances in CFD, parametric modeling, and optimization workflows now enable early design decisions that balance aesthetics, cost, safety, and sustainability. Overall, aerodynamic optimization is emerging as a foundational methodology for future high-rise development, ensuring that increasingly taller structures remain resilient, efficient, and human-centric.

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