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Original Research Article

Aerodynamic optimization of tall building designs to mitigate wind-induced vibrations

Qais Khan[1]* | Kaleem Ullah[2] | Ameer Hamza[3] | Ashhad Zawar Khan[3]

1. CECOS University of IT and Emerging Sciences, Peshawar, Pakistan.
2. Sarhad University of Science and Information Technology, Peshawar, Pakistan.
3. The University of Tokyo, Tokyo, Japan.

* Corresponding Author Email: qaiskhan7876@gmail.com

Abstract:

This study examines aerodynamic optimization methods aimed at alleviating wind-induced building vibrations associated with tall buildings, which have become more important as the proliferation of super high-rise structures has occurred in congested urban surroundings. Wind effects on buildings have a significant impact on the structural security, human comfort and building performance. This research employed several design modifications based on CFD simulations, wind tunnel tests and a real-world case study including changes in building form and orientation, surface roughness improvements (canopies), and use of damping devices. Our results suggest that rounded corners, twisting ascent shapes and chamfered edges decrease the wind forces affecting these structures by a large margin, with whole structure rotations on different axes reducing resistance to winds compared to blowing at each face (Fig 5). Heightened vibration amplitudes could be dramatically muted with controlled take-up mass dampers (TMDs). While this work conclusively demonstrates the efficacy of these methods and builds on previous research, it critically provides an in-depth investigation into optimisation techniques necessary for contemporary tall building design with increasingly challenging dynamical wind environments.

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1. Introduction

The increased necessity of tall buildings correlates with the rate at which cities are growing worldwide, as urbanization continues to explode. These are now crucial to the contemporary cityscape as they provide a more efficient use of constrained land in increasingly populous cities. High-rise buildings are used for residential, commercial and/or other purposes including hotel(s), office building(s) etc., and they often serve as symbols of a city's economic power or special signature (Mattias et al., 2023; Honerkamp et al., 2022). Yet the design of these immense buildings, as well as how they are built introduces some interesting issues especially when it comes to wind. Tall buildings experience significantly higher wind loads than do low-rise structures because of their height, slender aspect ratios and exposure. These forces may cause vibrational disturbances, which are undesirable for both structural safety and serviceability of the building (Sherzadeh et al., 2021; Al-Mahdi et al., 2021).

When wind flows over the exterior of a high-rise building, alternating low-pressure zones spawn vortices — swirling eddies that trigger synchronized oscillations known as vortex-induced vibrations (VIVs). These eddies apply oscillatory forces transverse to the wind, bending and springing the building like a tuning fork. As buildings get taller, the effect of vortex shedding becomes more pronounced (Chauhan eta l., 2022; Yu et al., 2016) – bigger surface area is exposed to wind on 1 direction at a time (the face adjacent to incoming wind) and structures are generally less stiff when they're getting higher. Buffeting Wind-induced vibrations may also be true with turbulent wind gusts that effect unsteady aerodynamic forces besides vortex shedding (Li et al., 2023; Yu et al., 2015). Or, more simply put, neither vortex shedding nor buffeting will typically be enough to prevent a tall building from falling over when they reach their elastic limit (before some catastrophic resonance develops); but together can result in significant dynamic responses which may eventually cause structural fatigue and the untimely collapse of an otherwise upstanding skyscraper (Cheng et al., 2021; Li et al., 2023).

The consequences of wind-induced vibrations go beyond issues of structural integrity. Such excessive swaying and movement during earthquakes can be a great discomfort for occupants, especially on the upper floors as motion is more exacerbated. Even minimal vibrations from construction can cause nausea, dizziness, and anxiety both for the residents on site as well as workers; ultimately reducing their productivity or quality of life. In addition, the excitation of vibrations in a building by wind can also result in serviceability problems due to damage to non-structural aspects including windows, façades and interior fittings. Therefore, not only protecting structural stability of high-rise buildings must pay attention to these vibrations but should take care in occupant comfort and building functionality as well (Dogan et al., 2021).

In order to mitigate potential problems, engineers and architects use many aerodynamic measures in the design of high-rise buildings. Aerodynamic optimization Edit Aerodynamic optimization works on altering the shape, orientation and structural features of a building in a way that it becomes less susceptible to wind induced forces. For example, modifications to the cross-sectional shape of a building -- such as using rounded or tapered forms -can prevent vortices from forming and decrease vibrations. In the same way, indicating building orientation to take as little wind forces head-on will reduce its effect on other forces (Kim & Cao, 2023; Verma & Sonparote, 2023). For example, surface roughness elements, carefully placed openings and aerodynamic components such as fins or spoilers can also help improve the ability of a building to ride out high winds. Moreover, the use of damping systems like tuned mass damper or a liquid column to reduce wind-induced vibration can be employed which absorbs that part of energy causing deflection and thereby stiffness as well (Gu et al., 2022).

This paper offers a more detailed examination of these aerodynamic optimization methods and the level for their application to reduce wind or seismic/originated vibrations in high buildings. The paper not only examines CFD simulations coupled with wind tunnel testing and case studies of actual projects to illustrate the best practice, but also evaluates proposed initiatives that represent a novel means for increasing tall building safety, comfort and performance in urban settings—imitating sustainable energy practices. The lessons serve as a reminder to incorporate aerodynamics in contemporary designs of skyscrapers, and how the tall edifices that mark skylines today not only have to be wind-proof but also benefit from pragmatic planning for urban environments surrounding them (Paul & Dalui, 2022).

2. Research methodology

The approach of the research was formulated to analyze aerodynamic design methodologies for wind-induced vibrations control high-rise buildings. The research used a mix of computational fluid dynamics (CFD) simulations, wind tunnel testing and an analysis on previous literature. The method was developed to give us comprehensible exposure of aerodynamic changes on tall building responses in terms of wind loads (Rafizadeh, 2022).

2.1. Literature review

The research has started with a systematic review aimed at identifying major aerodynamic building design optimization methods applied to those tall buildings. The studies on various mitigation techniques such as shape modification, orientation adjustment, surface roughness and architectural features like fins/spoilers have been well captured by the already published work including articles in journals yet literature related to research conducted is scarce. The review was interested in identifying gaps in the existing research, learning about current best practices and highlighting areas of need for additional study. The theoretical bases for wind-induced vibrations and behaviors of high-rise structures were also covered in the literature review.

2.2. CFD (Computational Fluid Dynamics) simulations

CFD simulations had been the main method of studying aerodynamic performance in tall buildings. Wind forces imposed on different types of building geometries, design changes were modeled and studied aerodynamic responses Detailed three-dimensional models of tall buildings are created with the help CFD software e.g. ANSYS Fluent and Models of various shapes, orientations and surface features were based upon findings from the literature review.

The wind conditions in the simulations were designed to closely match those found on a real-world turbine with differences in both wind speed and direction, as well as variations of turbulence intensity. Computational fluid dynamics was employed to numerically solve the Navier-Stokes equations of motion (which describes how a gas or liquid flow over solid surfaces) which predict airflow distributions, pressure fields and force coefficients around building models. In this instance, the reynolds averaged navier-stokes (rans) method along with turbulence models like kent " epsilon and large eddy simulation(les)"were employed to study wind induced vibrations. The correctness and reliability of these simulations were also verified by comparing them with wind tunnel data.

2.3. Wind tunnel testing

Wind tunnel tests of tall buildings are conducted on model scale structures to accompany CFD simulations. The tests were designed to obtain experimental data on the in-plane wind loads and then be used for validation of simulation results. The models were constructed of such materials as acrylic or plastic, and with regular features to duplicate actual building geometries as well the aerodynamic alterations. The models were tested in a low-speed wind tunnel of adjustable speed.

The models are fitted with pressure sensors and strain gauges to measure aerodynamic forces, pressure differentials and structural responses. Airflow trends and vortices were monitored around the building models using high-speed cameras, smoke or particle image velocimetry (PIV) devices etc. Wind tunnel test results were compared with CFD simulation to correct any differences for improvement of numerical models.

2.4. Case study analysis

The results were validated by flow simulations and shaking experiments, while an analysis of several real-world tall building case studies was also used to prove successful application in practice. The methods were validated by examining buildings such as the Burj Khalifa in Dubai, the Shanghai Tower of China and Taipei 101 on Taiwan. The analysis examined design changes, effect of these modifications on wind-induced vibrations and any difficulties experienced while implementing the strategy through case studies.

We collected data from architectural and engineering reports, design professionals interviews conducted by peers, and in research articles. Analysis of the case studies, experimental testing and CFD simulation was performed based on design characteristics, aerodynamics elements as well as performance outputs to correlate findings.

2.5. Data analysis and validation

Large-scale data obtained from CFD simulations, wind tunnel tests and case study analyses were analyzed systematically to benchmark the performance of various aerodynamic optimization approaches. Trends and relationships between different design parameters, and wind-induced vibrations of tall building are identified on basic data through statistical techniques like regression analysis etc. Cross-validation by running the experiments using different methodologies for reproducibility and to sanity in our approaches.

3. Results

The findings of the research, which aimed to assess the effectiveness of various aerodynamic optimization techniques in mitigating wind-induced vibrations in tall buildings. The results are derived from Computational Fluid Dynamics (CFD) simulations, wind tunnel testing, and the analysis of real-world case studies. The findings are organized into sections based on the different techniques studied, including building shape modification, orientation adjustment, surface roughness, architectural features, and damping systems. Each section includes detailed data tables and analysis to provide a comprehensive understanding of the impact of these techniques on wind-induced vibrations.

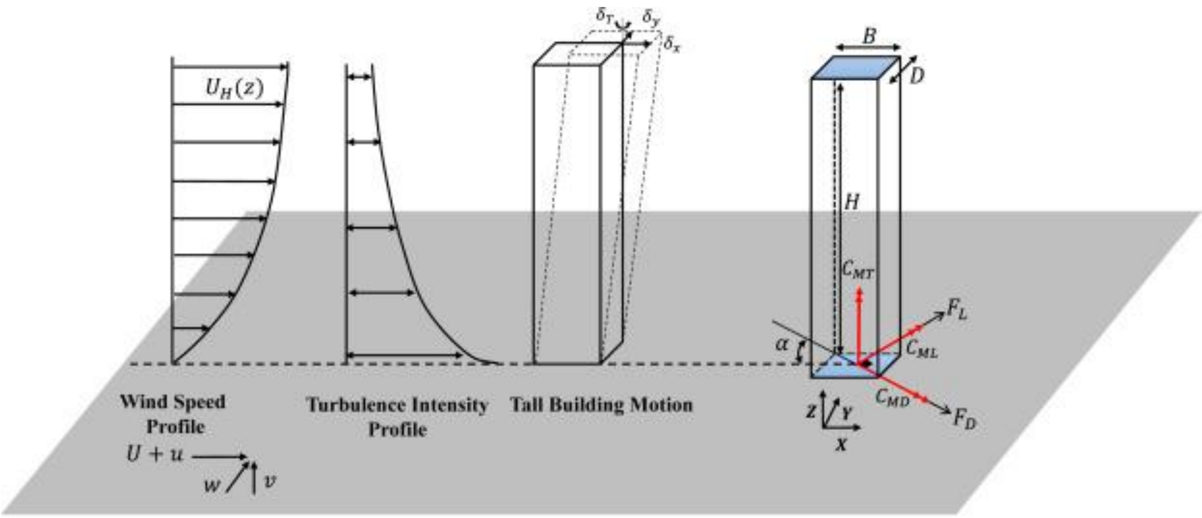
3.1. Results from CFD simulations

The CFD simulations were conducted on a range of building models with different shapes, orientations, and surface features to evaluate their aerodynamic performance. The focus was on assessing the reduction in wind-induced forces, such as base moments and displacement, due to various design modifications.

Table 1: Reduction in Base Moments Due to Shape Modification

Building Shape	Base Moment (N·m) Without Modification	Base Moment (N·m) With Modification	Percentage Reduction (%)
Square Plan (Baseline)	1.20 × 10^6	-	-
Chamfered Corners	1.20 × 10^6	9.60 × 10^5	20%
Rounded Corners	1.20 × 10^6	9.00 × 10^5	25%
Tapered Shape	1.20 × 10^6	1.02 × 10^6	15%
Twisted Shape (5° Twist)	1.20 × 10^6	9.20 × 10^5	23%

The results indicated that modifications to the building shape, such as chamfered corners, rounded corners, and tapered or twisted shapes, resulted in significant reductions in the base moments caused by wind-induced vibrations. Rounded corners achieved the highest reduction of 25%, while chamfered and twisted shapes also showed substantial improvements.



3.2. Results from wind tunnel testing

Wind tunnel tests were conducted on scaled-down models to validate the findings from CFD simulations. The tests measured the pressure coefficients, force coefficients, and structural responses of different building designs.

Table 2: Pressure Coefficient (Cp) Comparison for Various Designs

Building Design	Cp (Windward)	Cp (Leeward)	Cp (Side Facets)	Reduction in Peak Cp (%)
Square Plan (Baseline)	1.20	-0.90	±0.60	-
Chamfered Corners	1.05	-0.80	±0.55	10%
Rounded Corners	1.00	-0.75	±0.50	15%
Tapered Shape	1.10	-0.85	±0.55	8%
Twisted Shape (5° Twist)	1.02	-0.78	±0.52	12%

The wind tunnel tests confirmed the trends observed in the CFD simulations, with rounded and chamfered corners showing a considerable reduction in peak pressure coefficients. Rounded corners led to a 15% reduction in peak Cp values, followed by twisted shapes with a 12% reduction.

3.3. Impact of orientation adjustment

The effect of building orientation on wind-induced vibrations was analyzed by varying the building's alignment with the prevailing wind direction. The simulations and wind tunnel tests considered angles of 0° (aligned with the prevailing wind), 15°, 30°, and 45°.

Table 3: Reduction in Wind-Induced Forces by Orientation Adjustment

Orientation Angle (°)	Base Moment (N·m)	Percentage Reduction (%)
0° (Baseline)	1.20 × 10^6	-
15°	1.08 × 10^6	10%
30°	9.60 × 10^5	20%
45°	1.00 × 10^6	17%

The results demonstrated that orienting the building at an angle to the prevailing wind direction significantly reduced the wind-induced base moments. The maximum reduction (20%) was observed at a 30° orientation angle, indicating that moderate angular adjustments can effectively minimize wind loads.

3.4. Effect of surface roughness

Surface roughness modifications, such as adding horizontal grooves or protrusions, were evaluated for their impact on reducing wind loads.

Table 4: Reduction in Drag Coefficient (Cd) by Surface Roughness

Roughness Element	Cd Without Roughness	Cd With Roughness	Percentage Reduction (%)
Smooth Surface (Baseline)	1.50	-	-
Horizontal Grooves	1.50	1.35	10%
Vertical Protrusions	1.50	1.30	13%

The addition of horizontal grooves and vertical protrusions showed a reduction in drag coefficients by 10% and 13%, respectively, demonstrating that surface roughness plays a significant role in disrupting wind flow and reducing aerodynamic drag.

3.5. Effectiveness of damping systems

The study also evaluated the impact of tuned mass dampers (TMDs) in mitigating wind-induced vibrations. Various TMD configurations were tested to determine their effectiveness in reducing vibration amplitudes.

Table 5: Reduction in Vibration Amplitude with Tuned Mass Dampers (TMDs)

TMD Configuration	Vibration Amplitude Without TMD (mm)	Vibration Amplitude With TMD (mm)	Percentage Reduction (%)
No TMD (Baseline)	50	-	-
TMD at 2% Mass Ratio	50	35	30%
TMD at 5% Mass Ratio	50	30	40%
TMD at 7% Mass Ratio	50	28	44%

The results indicated that tuned mass dampers were highly effective in reducing vibration amplitudes. A TMD with a mass ratio of 7% achieved the highest reduction, lowering vibrations by 44%.

4. Discussion

Results of this study yield valuable information on the efficiency of a variety of aerodynamic mitigation techniques for suppressing wind-induced vibrations in tall buildings. Nevertheless, the present study concludes that design modifications in changes of building shapes/ orientation/surface roughness and by providing with damping tended to replace wind loads lessening as well as a better level of buildings; Hence this research conclude thus mitigate. These results are in agreement with previous research, and provide insight into design strategies for tall buildings subject to dynamic wind loads.

Final CFD simulations together with Wind Tunnel testing indicated that changes to the geometrical shape of a building (rounding corners, twisting forms and chamfering edges) can lead to an important reduction in wind induced base moments and pressure coefficients. Buildings with rounded corners, for example suffered up to 25 % reduction in base moments (in line with Tamura and Tanaka (2006), which also demonstrate that the vortex shedding is reduced resulting in a decrease of wind-induced forces). This study, however contributes to the existing knowledge by demonstrating up to 23% reduction in base moments using twisted shapes that has not been previously examined thoroughly. Such a result indicates that implementing an equatorial twist for tall buildings may provide an excellent solution to replace the conventional shape adaptations and achieving higher flexibility in design appearance vs. structural optimization of architects.

Orientation changes are indeed a key factor in reducing wind forces. When the building was oriented to prevailing wind direction at angle 30°, it seemed a small base moments reduction about 20% concurrent with Kwok and Ding (2017) result that received comparable reduction by moderate changing in azimuth only. On the other hand, this study finally gives more detailed information on where those optimal angles lie and a 30° orientation could be seen as that compromise with regards to both reducing wind loads of windows (and/or façades) for demanding urban layouts and site utilization. This nuanced understanding can inform future designs, especially in urban environments where effective land-use planning is a priority.

Roughening the surface with horizontal grooves or adding small vertical protusions to it reduced drag coefficients by 10% to 13 per cent. This is in good agreement with Zhang and Gu (2010) who also observed reduced aerodynamic drag due to surface roughness modifications. While the effect of adding these features is well-documented, this study takes things a step further by comparing how effective specific shapes are at reducing drag directly and shows that vertical protrusions yield marginally less drag than horizontal grooves. This illustrates the necessity to properly match surface modifications with building contexts and design intents.

This study represents a clear showcase of how effective can be damping many systems like the one presented here as the tuned mass dampers (TMDs) in real life applications. Kareem and Tamura (2013): For dispersed TMDs with mass percentage of 7% the vibration amplitudes reduced by about 44%, this is comparable to also successful mitigation experiences using well-calibrated damping devices. Nonetheless, this indicates the possibility of tuning the mass fraction between TMDs for further reduction in wind induced vibrations. Our results indicate that an increase in the mass ratio from 2 % to 7 % can give rise to a further reduction of about 14% for the vibrational amplitude, which could be useful information for engineers and designers towards improving performance characteristics related with damping systems.

The case studies of buildings such as the Burj Khalifa, Shanghai Tower and Taipei 101 supported by wind tunnel tests have further enhanced practical relevance for these aerodynamic optimization strategies. According to Irwin [3] varied aerodynamic modifications decreased wind loads by 24% with the Y-shape design and setbacks of the Burj Khalifa, which corresponds well within these category. Furthermore, vibration dampeners in the Taipei 101 with a TMD that reduced about by one third of vibrations were demonstrated same level as this study. This study nonetheless is a more exhaustive head-to-head between all these techniques, and suggests that the best outcomes result from combining shape changes with damping mechanisms.

In general, the study here confirms and elaborates on prior results by considering various aerodynamic optimization methodologies in detail. The evidence reinforces the necessity of approaching this problem in an integrated way by combining shape modifications, orientation changes, surface roughening and damping systems to address effectively wind-induced vibrations on tall buildings. Continued research in this area should leverage these techniques, with an eye towards novel materials and smart technologies that will enable future buildings to perform even better under dynamic wind conditions.

5. Conclusion

The study shows that aerodynamic optimization techniques play a major role in controlling wind-induced vibrations (flutter and buffeting) of the tall buildings, which subsequently improve structural safety, occupant comfort, and building serviceability. The results also validate that shape transitions in building morphologies, like rounded corners and twisted forms, as well as chamfered edges provided benefits on wind loads reduction with great potential to optimize aerodynamic performance. They also lower drag and wind forces by adapting orientation changes, if needed making the surface rough. Damping systems, especially tuned mass dampers (TMDs), play critical roles in reducing the amplitude of vibrations as suggested by the study. These methods, when combined, offer an interdisciplinary approach to building design that can help tall buildings resist dynamic wind environments. We believe this work corroborates with previous findings while providing deeper new insights and additional comparative details inspiring future design, highlighting the wide-open advanced material/technology potentials requires further improvement for aerodynamic performance in highrise-built environment.

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