

Integrated Parametric Design Framework of Super-Slender Buildings with Wind Escape Floors

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Summary

The rapid urbanization and scarcity of land in global financial centers have led to the emergence of "super-slender" high-rise buildings. These structures, characterized by slenderness ratios exceeding 1:10, are exceptionally sensitive to wind-induced excitations. This study introduces an integrated computational design tool tailored for the early design phases, where critical decisions regarding building form and structural systems are made. The tool links parametric geometric modeling with Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analysis within a unified environment. By automating the data transfer between these domains, the framework allows for the rapid evaluation of wind mitigation strategies, such as Wind Escape Floors (WEF). The tool's efficacy is demonstrated through validation against the CAARC standard building and a comprehensive case study of a 360-meter tower. The results highlight the potential of multidisciplinary integration in achieving aerodynamic efficiency and structural reliability without compromising architectural vision.

Keywords: *super-slender buildings, wind escape floors, architectural design, CFD, FEA*

1 INTRODUCTION

The architectural landscape of contemporary global metropolises is increasingly defined by "super-slender" high-rise structures. These buildings, often characterized by aspect ratios exceeding 1:10, present unprecedented challenges to structural integrity and occupant comfort due to their pronounced sensitivity to dynamic wind excitations. In such typologies, wind loads take place of seismic considerations as the primary design driver, necessitating a rigorous evaluation of aerodynamic responses at the earliest stages of development.

Despite the critical nature of wind-structure interaction, traditional architectural workflows often exhibit a fragmented relationship between formal exploration and engineering verification. Sophisticated wind engineering analyses, ranging from physical wind tunnel testing to high-fidelity Computational Fluid Dynamics (CFD), are typically conducted through a sequential design approach. Consequently, the ability to optimize the building's aerodynamic profile is frequently constrained, often necessitating substantial structural reinforcements or the integration of supplementary damping systems to satisfy stringent safety and serviceability criteria.

This research addresses this disciplinary disconnect by proposing a computational design framework that facilitates the integration of wind load assessments into the conceptual design phase. The study focuses on the implementation of "Wind Escape Floors" (WEF) as a strategic aerodynamic intervention to mitigate wind-induced forces in super-slender buildings. By establishing a unified parametric environment that bridges geometric modeling, aerodynamic simulation, and structural analysis, the developed tool enables a comprehensive understanding of the complex interactions between building morphology and structural response. This integrated methodology aims to provide designers with quantifiable performance metrics to ensure that aerodynamic efficiency and structural reliability are harmonized from the outset of the architectural process.

2 BACKGROUND AND METHODOLOGY

The evaluation of wind-induced effects on tall buildings has traditionally necessitated a choice between full-scale on-site experimentation and reduced-scale wind tunnel testing. While full-scale measurements capture the inherent complexity of the environment, they remain impractical for the iterative requirements of the design phase due to uncontrollable environmental variables. Conversely, while wind tunnel testing provides reliable data, its application in the optimization process is frequently constrained by significant temporal and financial requirements (Stathopoulos, 1997; Blocken and Stathopoulos, 2013; Blocken, 2014). Consequently, the integration of Computational Fluid Dynamics (CFD) and Fluid-Structure Interaction (FSI) into the wind engineering domain has emerged as a transformative alternative. These numerical methods facilitate the acquisition of whole-flow field data under controlled conditions, though they necessitate rigorous validation and verification due to their high sensitivity to user-defined parameters such as turbulence models and mesh configurations (Thordal et al., 2020). Despite the growing maturity of computational methods, a critical research gap persists regarding the interdisciplinary optimization of "Wind Escape Floors" (WEF) during the conceptual design stage. Current literature indicates that although the aerodynamic benefits of WEFs have been examined through various methods over several decades (Dutton and Isyumov, 1990; Moorjani et al., 2021), these features are often treated as non-functional architectural voids rather than integrated performance-driven components. Failure to synchronize the positioning of WEFs with structural reinforcements, such as outrigger systems, during the initial design phases often leads to significant design revisions and financial losses (Elshaer and Bitsuamlak, 2018). Thus, there is an urgent need for sophisticated, multidisciplinary frameworks that enable architects and engineers to consistently evaluate the synergy between aerodynamic mitigation and structural efficiency before the design becomes finalized. The proposed methodology is centered around a modular computational framework developed within a parametric environment (Rhinceros/Grasshopper). The workflow shown in Figure 1 automates the data mapping between geometric generation, aerodynamic simulation, and structural analysis to provide near-instantaneous performance feedback.

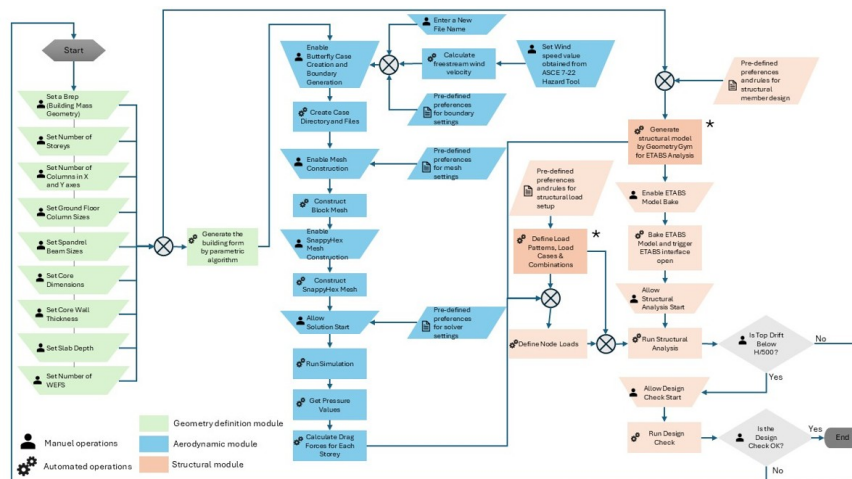


Figure 1: Flowchart of the integrated Design Tool

2.1 Parametric Geometric Modeling and Morphological Variation

The geometric module utilizes algorithmic definitions to generate building envelopes where the slenderness ratio and height are primary variables. A dedicated sub-module manages the parametric configuration of "Wind Escape Floors" (WEF), allowing for the systematic variation of number of WEF's and outriggers, vertical positioning of them, and structural member sizes and locations. This setup enables the generation of a vast design space for iterative performance testing.

2.2 Aerodynamic Assessment (CFD Integration)

For the aerodynamic module, the OpenFOAM solver is utilized via the Butterfly interface. To ensure a strategic trade-off between computational efficiency and simulation accuracy—essential for early-stage design exploration—a steady-state Reynolds-Averaged Navier-Stokes (RANS) approach with a k-epsilon turbulence model is implemented. The module automates the computational domain generation and meshing processes, extracting surface pressure coefficients (C_p) and velocity profiles directly from the building's parametric geometry.

2.3 Structural Performance Module (FEM Integration)

The structural module facilitates the automated mapping of extracted pressure data onto a Finite Element Method (FEM) model within ETABS. Using the GeometryGym plugin, the tool constructs the structural skeleton, including core-wall systems and outrigger configurations, synchronized with the architectural geometry. This integration allows for the quantitative assessment of critical structural responses, such as maximum lateral displacement ($H/500$ limit) and base moments, directly resulting from the simulated wind loads. Also, this module can check the design loads for structural frame members and core walls.

3 RESULTS, DISCUSSION AND CONCLUSION

3.1 Validation and Verficiation

The preliminary phase of the research focused on the rigorous validation of the integrated computational tool. Structural load verification was conducted using a 60-meter rectangular prism tall building, where story drift values calculated by the developed tool were compared against code-based assessments (ASCE 7-16). The analysis demonstrated an exceptionally high correlation with a coefficient of $R = 0.9$, confirming the tool's reliability in mapping aerodynamic pressures to structural responses. Furthermore, aerodynamic validation was performed using the 180-meter CAARC standard tall building model. The mean pressure coefficient (C_p) distribution obtained through the OpenFOAM-based module showed a strong agreement with established experimental data and previous numerical studies in the literature. The flow patterns captured around the CAARC building, specifically the wake region and vortex shedding characteristics, aligned with standard Computational Wind Engineering (CWE) benchmarks, establishing a credible foundation for the subsequent parametric investigations.

3.2 Parametric Investigation of WEF's

The tool was implemented on a 360-meter super-slender building (aspect ratio 1:12) to evaluate five distinct design alternatives. The baseline models (Alternatives 1 and 2), which relied solely on increasing column cross-sections, failed to meet the $H/500$ serviceability threshold for lateral drift.

Although the introduction of a standalone structural outrigger system (Alternative 3) significantly enhanced rigidity, the building remained subject to high-intensity aerodynamic drag forces. The introduction of a Wind Escape Floor (WEF) in Alternative 4 successfully reduced the total lateral wind force. However, the most effective strategy was identified in Alternative 5, which utilized a synchronized architectural and structural intervention. By integrating both a WEF and an outrigger at the same vertical level, the design achieved a dual benefit: the WEF reduced the input wind load while the outrigger provided the necessary response stiffness to keep oscillations within acceptable limits. (see Figure 2)

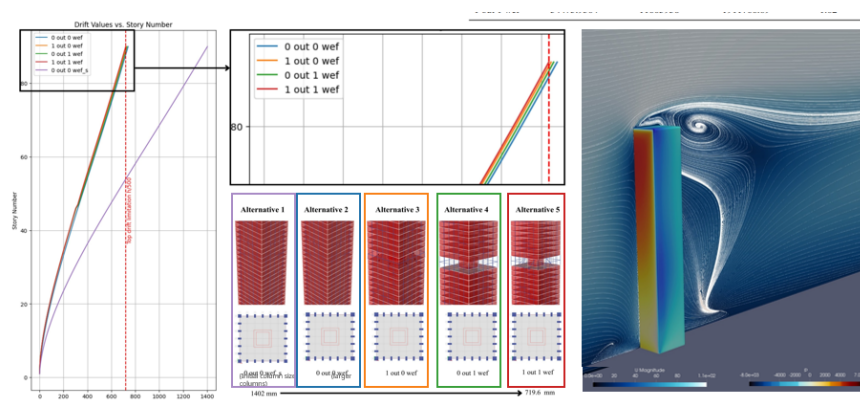


Figure 2: Top drift values and flow around the building

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