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Parametric design-based aerodynamic shape optimization of tall buildings

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SUMMARY:

Wind effects have a significant impact on the design of slender structures. In tall buildings, serviceability accelerations are often the design governing criteria, and the building shape and aerodynamic characteristics play a significant role in achieving the optimum design case. This work investigates the use of parametric design tools to accelerate the initial design phase of high-rise buildings while accounting for CFD simulations. Implementing parametric design and machine learning tools into aerodynamic shape optimization is verified. In addition, wind analyses regarding the aeroelastic phenomena and design criteria for high-rise buildings are discussed in terms of human comfort accelerations. The implementation of the analysis workflow is applied to a high-rise building project. First, the parametric design modeling of the structure is performed, carrying out the data automatically for the structural analysis software and the CFD solver. In the sequence, the wind analyses are performed for different building architecture variations, and the machine learning methodology is implemented to determine the optimum building solutions for serviceability accelerations.

Keywords: parametric design, tall buildings, optimization

1. INSTRUCTION

In the last decades, the human desire for taller structures and incredible skyscrapers brought the enormous challenge of making it possible regarding structural design, especially related to wind design. Tall buildings, especially, are very sensitive to building shape, structural properties, wind speed, and one of the most common ways to mitigate accelerations is by modifying the building shape (Denoon, 2019). In order to reach an optimum design and avoid serviceability problems, a substantial amount of numerical simulations and wind tunnel tests are necessary. Therefore, it is crucial to have strong cooperation among the design team, creating optimization opportunities from the beginning of the project and enhancing the design's final performance.

2. METHODOLOGY

Established in Rhino/Grasshopper, a parametric approach was incorporated to define initial parameters that serve as the basis for the structural definition in the structural solver and CFD analysis files creation in the flow solver, using Vortex Particle Method Implementation. The parameter control interface was used to obtain, in an automated way, the dynamic structural properties, aerodynamic characteristics, and ultimately the response due to a simulated wind flow, from which the acceptance criteria can be compared. Figure 1 displays the complete flow process development.

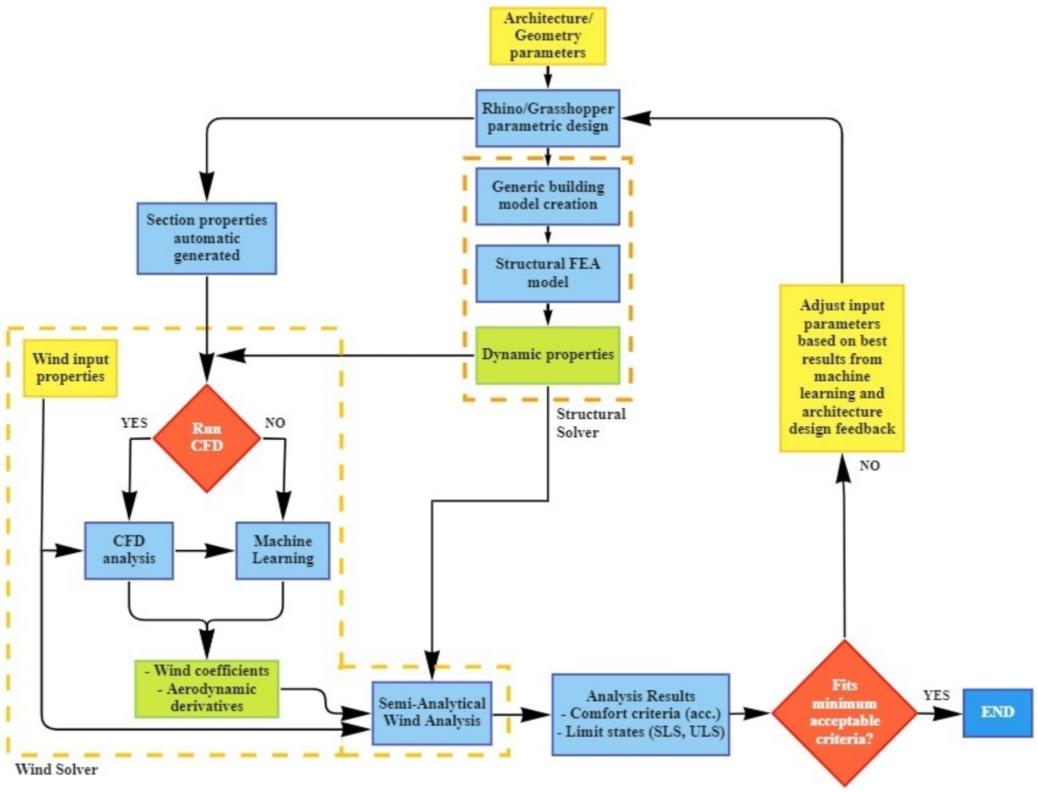

Figure 1. Flowchart of process development, software loop and integration.

3. CASE OF STUDY

The analyses were performed in a very slender and tall building. Wind tunnel results were used as a comparison and wind design evaluation. The 3D image of the building model is shown on Figure 2 (a). The tower's height is 431 meters, counting 108 floors, some on the top only used as a reference plane, and the building's first modal frequency is 0.097Hz. The building slenderness ratio is around 1:13, situated in Dubai.

3.1. Parametric Design Modeling - Structural and CFD

The main objective of using parametric design was to reduce initial design time and create directly from the main file, the basic structural design file for numerical analysis, and the CFD files for aerodynamic analysis.

With the completion of the visual code sequence, the changes in geometry could be easily incorporated since the model worked parametrically for the structural analysis and automatically according to the outer geometry shape for the CFD analysis, generating the models in a short time and enabling faster initial input. An illustration of the visual code, structural design model, and CFD model are shown on Figure 2 (b), (c), and (d), respectively.

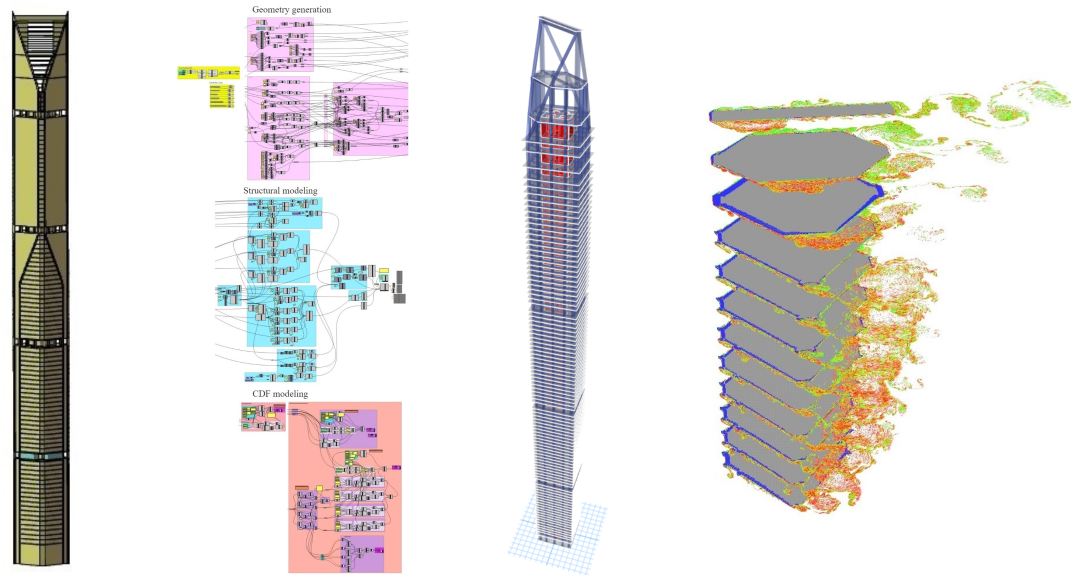

Figure 2. **(a)** 3D model of the building. **(b)** Parametric design visual code for creating the models. **(c)** Structural analysis model. **(d)** Panel discretization illustration for building sections for CFD analysis.

3.2. Aerodynamic analysis

The wind examinations were performed by static and dynamic analyses to understand better the effect of shape variation on the building performance. In addition, the investigation considered the ultimate and serviceability limit states. Different sections were tested, considering chamfer variation, architectural details in the facade, top section reduction, and the possibility of opening floors over the height. Even though small, the architectural detail in the facade influenced the flow separation modifying the wind coefficients. The top reduction and open floor variation were the most significant changes. For the top reduction, the variation of wind effects was evident, especially regarding the wind angle of attack. The open floor changed wind effects considerably, reducing drag and changing the lift and moment behavior of the section.

When considering the serviceability limit state, one of the essential characteristics to be truly observed is the users' comfort, which is directly related to the acceleration of the building due to the wind loads. The international standard ISO-6897 presents guidelines for the evaluation of the response of occupants to low-frequency horizontal motion considering r.m.s acceleration, and it was used to set limits in this study.

Figure 3 compares the analysis performed with the original structural model (OD) and the parametric design building model (PD), the r.m.s. acceleration band shows the difference between both, especially on the top floor, which presents a particular shape. However, it is noticeable that the difference in the results is minimal, showing the loop works, and the difference is not remarkable to modify the characterization to the average perception limit, for example, especially for the building's first modal frequency (0.097Hz).

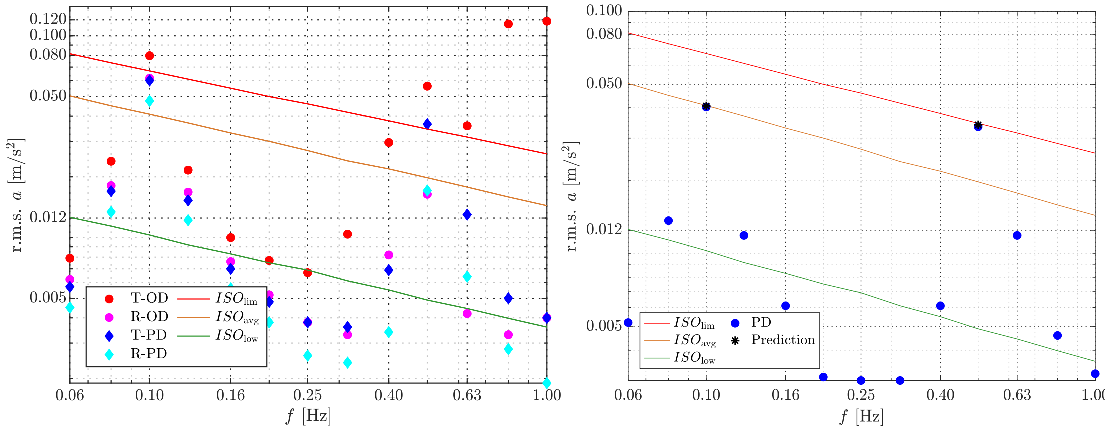

Figure 3. (a) Along-wind r.m.s. acceleration for (OD) and (PD) buildings on top floor (T, z=431.0m), and last residential floor (R, z=354.7m), T=5 years. ISO-6897 limit bound, average, and lower perception limits are shown for comparison. **(b)** R.m.s. acceleration (PD) and prediction, top floor (z=431.0m), T=5 years.

3.2.1. Machine Learning

Expanding the analysis further, the application of machine learning for the r.m.s. accelerations prediction improved, even more, the initial idea of this project, considering that with these interactions, it is possible to verify at each value of architectural modification that the accelerations present acceptable results without running the complete CFD analysis again. In addition, the machine learning interaction can be applied to evaluate any architectural change in size, evaluating its effect on the final design. Figure 3 shows results versus prediction for specified section evaluation.

4. CONCLUSIONS

The parametric design showed itself as a powerful tool for accelerating the design interaction process. Even minor shape modifications can impact aerodynamic wind effects. The proposed initial design loop presented smaller displacements and accelerations compared to the original one due to less structural refinement, although still very significant and helpful in the initial design phase due to the valuable comparison data it can provide. The machine learning process in the design increased the optimization opportunities. After all, the proposed loop can certainly enhance the initial phase design of tall buildings, even when applied partially, depending on the project needs and specific situation.

ACKNOWLEDGMENTS

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