August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

# City-Scale Time History Analysis of Tall Buildings: Computational Framework

Donglian Gu [1], Ahsan Kareem [2], Xinzheng Lu [3]

[1] *Research Institute of Urbanization and Urban Safety, School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing, China, gudonglian@ustb.edu.cn*
[2] *NatHaz Modeling Laboratory, University of Notre Dame, Indiana, USA, kareem@nd.edu*
[3] *Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China, luxz@tsinghua.edu.cn*

**SUMMARY:**
Central business districts are densely built with clusters of high-rise buildings that are exposed to winds, impacting their strength, serviceability, and habitability. A computational framework to perform the city-scale time history analysis of wind-induced vibrations of tall buildings was proposed in this work, while existing studies have been mostly limited to isolated building cases. The framework features (1) the large eddy simulation (LES) for time-varying wind loads on buildings, (2) a city-scale time history analysis to capture the response of buildings in a cluster, (3) a high-fidelity visualization of results, and (4) the city-scale performance assessment. A portion of downtown San Francisco is utilized to demonstrate the framework's potential to usher in a new era in the computational design and assessment of buildings for strength, serviceability, and habitability. The proposed framework offers to complement wind tunnel studies as a virtual twin by enhancing the provision to model building-cluster dynamics synchronously. The framework is designed to serve as a system-level computation-based analysis and design platform for building clusters, and does not necessarily aim to reflect recent advances in LES modeling. Each component of the framework is modular, and its fidelity can be enhanced by introducing any available refinement.

*Keywords: wind-induced building motion, tall building, city-scale time history analysis, 3-D dynamic visualization*

## 1. INTRODUCTION

High-rise buildings are an important part of the modern city. The central business districts (CBDs) of some cosmopolitan cities, e.g., Hong Kong, Shanghai, and New York, are densely built with clusters of high-rise buildings that experience complex interactions with wind generating complicated load effects that impact their performance, urban planning, and management.

The design of high-rise buildings in a cluster, which is one of the most important aspects of urban planning, faces the challenge of evaluating building performance under winds. In a CBD, the building configuration and its layout can change the wind field, thereby affecting the wind loads and their effects on buildings. Consequently, the design of a specific high-rise building in a CBD-like area warrants attention to the details of the surroundings, and it may also have an impact on the performance of surrounding buildings. In the design codes or standards of most countries, while the influence of the surroundings is often included in the simulation, no information is required to be provided to the existing buildings' management regarding the impact of the new building on the existing buildings. There are some exceptions, like Singapore. From this perspective, a city-scale assessment method of wind effects on buildings is necessitated to complement the preliminary design of high-rise building clusters. However, existing studies on wind effects on buildings are primarily focused on individual building levels [1-4]. To the best of the authors' knowledge, such holistic city-scale studies have not been done before due to the complexity and challenges involved. This study aims to fill this gap by introducing a novel computational methodology to evaluate building performance under wind effects at a city scale.

Targeting the abovementioned challenges, a computational framework for assessing the performance of buildings in winds at a city scale was proposed. A portion of Downtown San Francisco was used as a case study.

## 2. METHODOLOGY

The workflow of the proposed framework is outlined in Figure 1.

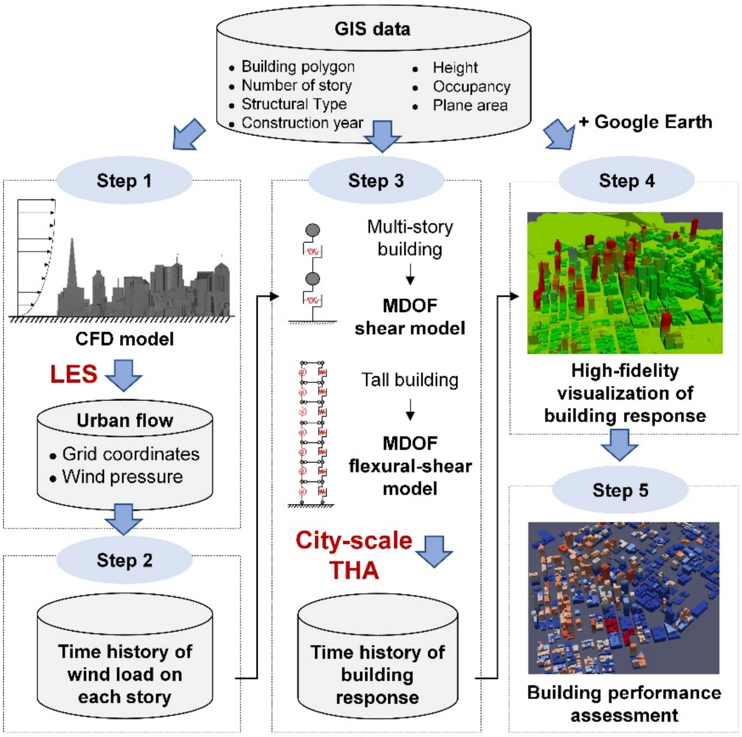


**Figure 1.** Proposed computational framework.

A geographical information system (GIS) was selected as the initial database for this framework. Specifically, seven types of building features, i.e., building polygon, number of stories, structural type, construction year, height, occupancy, and footprint area, are required in the GIS. This is followed by five steps to complete the entire process. (1) Step 1. The computational fluid dynamics model of the target area is constructed based on the building shapes information. Subsequently, the large eddy simulation is utilized to obtain the time history data of wind pressure field around buildings. (2) Step 2. The wind pressure data is transformed to the time-varying wind loads at building story levels. (3) Step 3. The buildings are modeled as multi-degree-of-freedom shear and flexural–shear models according to their structural characteristics. The city-scale time history analysis is performed following Step 2 to predict the wind-induced motion of each building concurrently. (4) Step 4. A high-fidelity visualization of the building motion is introduced based on the three-dimensional urban model (generated based on the GIS data and Google Earth) and the time history data of building response obtained in Step 3. (5) Step 5. The building response, including occupant comfort of each building, is assessed based on the dynamic building response utilizing a human comfort criterion. The modularity of the framework permits a user to invoke different structural models and comfort criteria they may wish to use. Details of the methodologies for each step are presented in the following sections.

Additional details of the underlying methodologies used in the abovementioned steps will follow in the presentation.

## 3. CASE STUDY

A case study for a portion of downtown San Francisco was performed to demonstrate the implementation of the proposed computational framework for regional applications. The study area is the core part of the CBD. It was chosen because a majority of San Francisco's high-rise buildings were located in this region. Specifically, 564 buildings were considered, which encompassed an area of approximately 4 $km^2$ (Figure 2a). The distribution of building heights is shown in Figure 2b, illustrating that the numbers of buildings higher than 100, 150, and 200 m are 55, 18, and 2, respectively. It is noteworthy that as construction in San Francisco has developed rapidly in recent years, the GIS data obtained in 2017, in this case, may differ from the present. Nevertheless, the case study offers a real-world application of the computational framework to a large cluster of buildings.


**Figure 2.** a) A view of downtown San Francisco, b) distribution of building heights.

A northwest wind, one of the main wind directions in San Francisco according to historical meteorological data, was selected as an example. Two wind intensities with mean recurrence intervals (MRI) of 700 years and 1 year were considered in this study. An animation of the building motions under the 700-year-recurrence scenario can be viewed directly at https://cloud.tsinghua.edu.cn/f/46f57e68c6584f24bca1, which can provide more intuitive information to facilitate the decision-making of nontechnical people, especially for the performance-based design. One of the important building performance measures under wind is the occupant comfort level. The occupant comfort criterion recommended by AIJ-GEH-2004 criterion [5] was used here for the occupant comfort assessment, given that it is aimed at performance-based wind design. AIJ-GEH-2004 uses the peak acceleration to evaluate occupant comfort and categorizes the comfort quality into five levels: H-10, H-30, H-50, H-70, and H-90, which represent 10%, 30%, 50%, 70%, and 90% of the persons in the building who can feel the wind-induced vibration, respectively. Other criteria like ISO or ASCE recommendations can be easily introduced.

The assessment results of all 564 buildings in the downtown San Francisco case are shown in Figure 3. Under the 700-year-recurrence wind, among the 55 buildings over 100 m, 87.3% of the buildings indicate an occupant comfort quality of H-90 on the top story. Hence, the northwest wind scenario with the MRI of 700 years is worth paying attention to for downtown San Francisco considering that the high-rise buildings accommodate a large number of people in the city. An assessment at this level of winds is currently not needed in design but was introduced to see how many buildings will be influenced when unusual winds are experienced, which is a question asked out of curiosity by stakeholders sometimes as well as the frequent strong winds in the area brought about by winter storms and bomb cyclones. By contrast, under the 1-year-recurrence wind, there are only two buildings whose occupant comfort qualities of the top story reach H-50, indicating that this wind scenario is considered to have a slight effect on the building function. Furthermore, it can be observed from Figure 3 that the occupant comfort quality of each story can be visualized with high fidelity through the proposed framework.

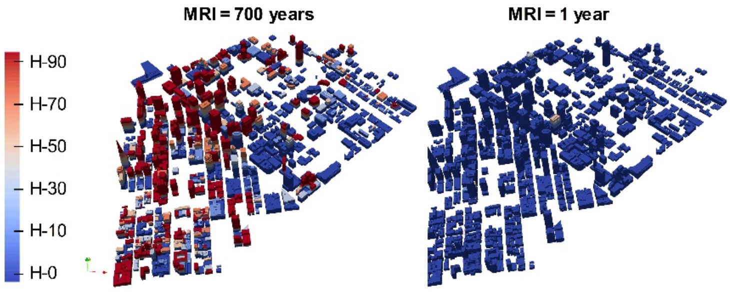


**Figure 3.** Visualization of occupant comfort levels for all 564 buildings.

## 4. CONCLUSIONS

A computational framework to perform the city-scale time history analysis of building clusters under winds was proposed in this work, while existing studies have been mostly limited to isolated building cases. A portion of downtown San Francisco is utilized to demonstrate the framework's potential to usher in a new era in the computational design and assessment of buildings for strength, serviceability, and habitability. The framework also offers mapping of the wind field around buildings at any level to perform pedestrian-level wind assessment.

**ACKNOWLEDGEMENTS**

This work was supported by the National Natural Science Foundation of China (No. 52238011, 52208456), the SimCenter under NSF grant CMMI 2131111, and the Tencent Foundation through the XPLORER PRIZE

**REFERENCES**

[1] Yan, B. W., & Li, Q. S. (2016). Large-eddy simulation of wind effects on a super-tall building in urban environment conditions. Structure and Infrastructure Engineering, 12(6), 765-785.

[2] Zhang, Y., Habashi, W. G., & Khurram, R. A. (2015). Predicting wind-induced vibrations of high-rise buildings using unsteady CFD and modal analysis. Journal of Wind Engineering and Industrial Aerodynamics, 136, 165-179.

[3] Braun, A. L., & Awruch, A. M. (2009). Aerodynamic and aeroelastic analyses on the CAARC standard tall building model using numerical simulation. Computers & Structures, 87(9-10), 564-581.

[4] Tamura, T., Nozawa, K., & Kondo, K. (2008). AIJ guide for numerical prediction of wind loads on buildings. Journal of Wind Engineering and Industrial Aerodynamics, 96(10-11), 1974-1984.

[5] Architectural Institute of Japan (AIJ). (2004). Guidelines for the Evaluation of Habitability to Building Vibration. AIJ, Tokyo.