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

Modeling Windborne Debris Flight Trajectory in Urban Communities

Yue Dong [1], Shaopeng Li [2], Kimia Y. Anarak [3], Ryan A. Catarelli [4], Yanlin Guo [5], Kurtise R. Gurley [6], John van de Lindt [7]

[1]Colorado State University, Fort Collins, USA, yue.dong@colostate.edu
[2]University of Florida, Gainesville, USA, shaopengli@ufl.edu
[3]Colorado State University, Fort Collins, USA, kimia.yousefi_anarak@colostate.edu
[4]University of Florida, Gainesville, USA, rcatarelli@ufl.edu
[5]Colorado State University, Fort Collins, USA, yanlin@colostate.edu
[6]University of Florida, Gainesville, USA, kgurl@ce.ufl.edu
[7]Colorado State University, Fort Collins, USA, john.van_de_lindt@colostate.edu

SUMMARY:
The non-structural building envelope components of high-rise buildings such as façade and cladding systems, especially the glass portion, often experience damage due to windborne debris during hurricanes. The key to evaluating the risk of debris damage in urban communities is modeling the mechanics of the windborne debris transport process. The existing debris damage analysis methods do not use an urban wind field; quantitative investigations of debris flight behavior under urban wind environments are lacking in current studies. Furthermore, change of debris flight trajectory in building clusters with the variation building configurations needs to be investigated to allow comprehensive understanding of windborne debris risk in urban communities with different building layouts. In this study, wind tunnel tests are conducted to (1) capture the complex wind velocity field over building clusters and (2) study the debris behavior in the urban environment. New approaches for modeming the trajectory of windborne debris in urban wind environment are proposed.

Keywords: windborne debris, urban wind field, PIV test

1. MOTIVATION

Building envelopes in urban areas may suffer severe damage during hurricanes and missile impact from windborne debris is one important damage source (Kareem, 1986; Kareem and Bashor, 2006). The failure of building envelopes pose a threat to the safety of occupants and induce the loss of building functionality and content damage. Efficient modeling of debris behavior for generic urban building clusters is critical for evaluating the risk of windborne debris in urban communities. However, the existing debris-impact models did not consider a realistic complex urban flow field (Lin et al., 2018). Furthermore, most numerical debris trajectory models only consider simple inflow conditions (Kakimpa et al., 2012) and the performance of these models for complex urban wind fields is unknown due to the lack of quantitative investigation. To bridge these gaps, wind tunnel experiments coupled with machine learning are employed to investigate the urban wind field and corresponding debris flight mechanism in this study. New approaches for modeling the debris flight trajectory in urban enviroment are proposed.

2. MODELLING URBAN WIND FIELD

The aerodynamic interaction between high-rise buildings and the surroundings is complex in urban communities and the wind tunnel test is an appropriate tool to simulate the wind field in urban areas. Realistic complex urban flow fields need to be considered in debris impact analysis through wind tunnel experiments with various building layouts.

2.1 Sampling of building cluster configuration

The building clusters considered in the study should be realistic and generic, and allow for feasible flow field measurement in the wind tunnel. The layout of the building clusters is determined by the number of buildings, and the height, geometry and location of each building. The direction of wind is also considered. As a resource intensive experiment, the number of studied building cluster configurations is limited. To reduce the dimension of the parameters of building cluter configuration, building clusters with two to six buildings are considered and only two critical parameters, location of buildings and inflow wind direction, are investigated while the other factors are fixed. Specifically, the location of buildings is determined by the relative distance and rotation angle between buildings. An example of one building cluster is shown in Fig. 1. A sensitivity analysis is conducted to enable efficient sampling of these location parameters. The sensitivity analysis is conducted by investigating the impact of these parameters on the wind field through Computational Fluid Dynamic (CFD) simulation with the Reynolds-Averaged Navier-Stokes (RANS) model.

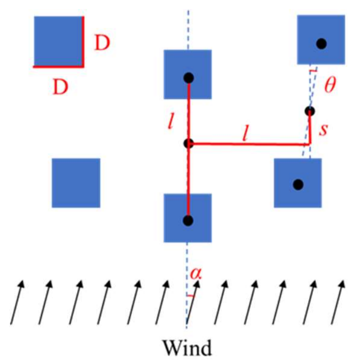

Figure 1. Example layout of tested building clusters.

2.2 Wind tunnel test for urban wind field

The experiments are conducted at the University of Florida boundary layer wind tunnel (UFBLWT) with a test section of 6 m wide and 3 m high. A three-component two-dimensional (3C2D) stereoscopic PIV is used to capture the wind flow velocity (Hui et al., 2017). The system consists of two high-speed cameras to measure the longitudinal, lateral and vertical velocity components at one laser-illuminated plane. The flow velocity field measurement will be achieved by moving the 2D laser sheet along the transverse direction sequentially to measure velocities at each laser-illuminated plane. In addition, multiple velocity probes are used to capture the lateral spatial correlation of wind velocity. The goal is the reconstruction of a 3D wind field including the temporal and spatial correlation structure. The structure of the 3D wind field is highly nonlinear according to the turbulence effect, thus, machine learning approaches that are successful as non-linear approximators are applied for the reconstruction of the 3D wind field. The performance of different deep learning approaches is investigated.

3. VALIDATION OF DEBRIS FLIGHT TRAJECTORY MODELS

Existing numerical models of compact and plate-type debris trajectories in 3D wind fields are developed with straight line wind and the performance of these models in urban wind fields should be tested. Thus, wind tunnel experiments are conducted to capture the 3D 6-degree-of-freedom (DOF) debris transport process in urban winds using a stereo-photogrammetry technique (Sabharwal and Guo, 2019) in this study. The experiment is also conducted in the UFBLWT.

3.1 Experiment setup

Both the compact and sheet-like debris that represent the most common type of debris found in urban areas are investigated. Simple building clusters with one debris source building and one interference building are adopted for producing the urban winds to minimize the building blockage effect and allow capturing the debris flight trajectory. The initial location of debris is on the rooftop or one vertical face of the source building considering various sources of debris, such as gravel and glass piece. The debris with zero initial velocity is attached to the electromagnetic strips and released with desired inflow wind conditions. A pair of high-speed cameras capture the debris flight trajectory and the 6D coordinates (3 translational and 3 rotational) are then calculated from pairs of stereoscopic 2D images of recored videos using a stereo-photogrammetry based on the computer vision technique developed by Sabharwal and Guo (2019).

3.2 Validation of debris trajectory models

A physics-based 3D 6DOF debris trajectory model using a time-marching algorithm (Abdelhady et.al 2021) is adopted to predict debris trajectory for complex turbulence urban winds. The 6D coordinates of debris at each time step are solved by the updating aerodynamic coefficients obtained from previous wind tunnel studies (Richards et al., 2008) and the wind velocity obtained from the aforementioned wind tunnel experiments for various building clusters (Section 2). The simulated debris flight trajectory is compared to the wind tunnel experiment results for validation. It should be noted that a larger length scale factor is used in the experiment of debris flight trajectory to enable feasible modeling of both buildings and debris compared to the experiment of the wind field. Thus, the scalability issue between the two types of wind tunnel experiments should be checked before applying the validated debris trajectory model to various building clusters tested in the previous section.

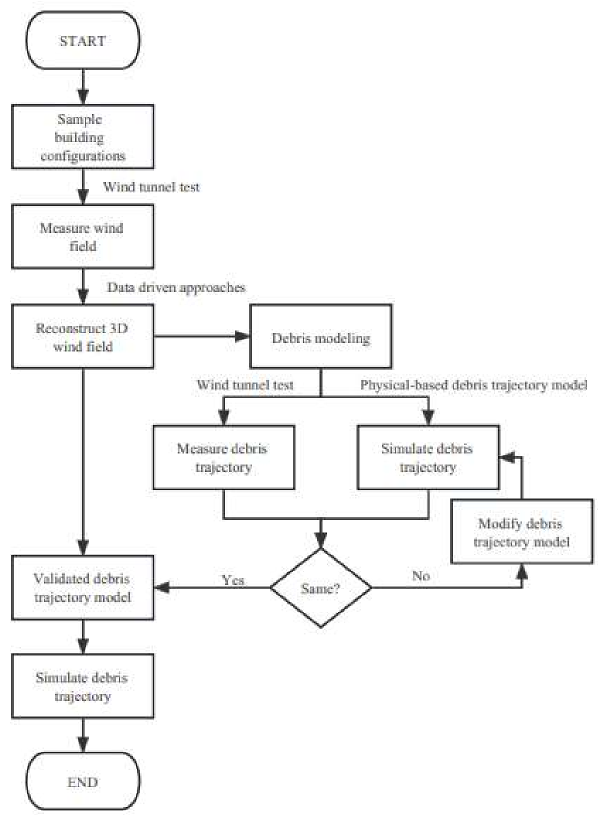

Figure 2. Flow chart for simulating debris trajectories in urban environment

CONCLUSION

The urban wind field for various building clusters and the behavior of windborne debris in the urban environment are studied through integrated wind tunnel experiments, machine learning and numerical modeling. The debris flight trajectories in the tested building clusters are simulated by coupling the measured wind field with numerical debris trajectory model. The modelling of debris flight behavior in urban winds is validated in the wind tunnel experiments. Fig. 2 summarizes the procedure of proposed methodology for simulating the windborne debris flight trajectory in various building clusters.

ACKNOWLEDGEMENT

The research herein was funded, in part, by National Science Foundation (NSF Grant No.: 2153751, 2153762 & NHERI Grant No. 2037725), as well as the Center for Risk-Based Community Resilience Planning, a Center of Excellence funded through a cooperative agreement between the U.S. National Institute of Science and Technology and Colorado State University (NIST Financial Assistance Award No.: 70NANB15H044 and 70NANB20H008). These supports are gratefully acknowledged. The views expressed herein are those of the authors and may not represent the official position of the National Institute of Standards and Technology or National Science Foundation.

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