

# Aerodynamic Loading under Progressive Envelope Failure using Large-Eddy Simulations

Jieling Jiang<sup>a</sup>, Seymour M.J. Spence<sup>b</sup>

<sup>a</sup>University of Michigan, Ann Arbor, Michigan, USA, jennyjll@umich.edu

<sup>b</sup>University of Michigan, Ann Arbor, Michigan, USA, smjs@umich.edu

## Summary

Most current assessments of building envelope performance assume that, although external pressures can damage envelope components, subsequent aerodynamic loads remain unchanged by these failures. However, envelope damage is closely related to local peak pressures, and significant loss of envelope components can redistribute pressure onto adjacent, remaining elements. Accurate assessment of both external and internal pressure fields as openings dynamically occur is therefore essential. To address this gap, this work couples a large-eddy simulation (LES) framework with a building envelope fragility model, capturing two-way interactions between envelope component failure and dynamic internal and external pressure fields. A two-story building is used as a case study to demonstrate the framework. The proposed approach enables more realistic simulation of progressive damage and advances performance-based wind engineering by modeling feedback between envelope loss and aerodynamic loading.

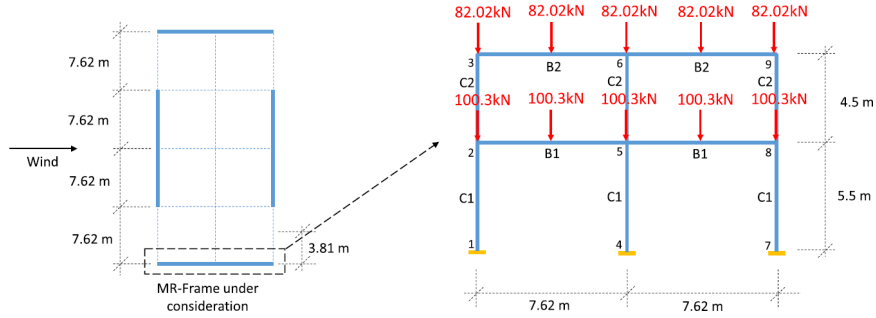
**Keywords:** *Progressive envelope failure, building aerodynamics, large eddy simulations*

## 1 INTRODUCTION

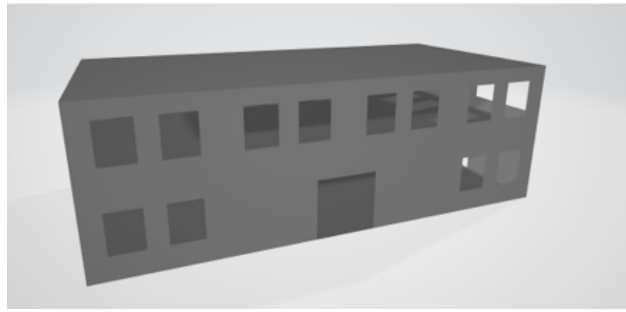
Severe wind events often cause catastrophic building damage, posing significant life-safety hazards and resulting in substantial economic losses. Notably, a large portion of these losses arises from failures in non-structural building envelope components, such as glass panels, which frequently trigger extensive interior damage due to wind-driven rain ingress (Sparks et al., 1994; Kareem, 1985). Various efforts have been made to address this concern (e.g., Ouyang and Spence, 2019; Ouyang and Spence, 2021; Wu et al., 2024); however, existing frameworks often assume that the loss of envelope components does not change the structural wind loads. In reality, the evolution of envelope damage is a progressive and dynamically coupled process. For example, the loss of envelope components on the windward face can increase internal pressure, thereby escalating the vulnerability of leeward and side envelope components subjected to suction effects due to the increased net pressure. In turn, excessive loss of envelope components can alter the aerodynamic loads acting on the structural system. Capturing this two-way coupling between the progressive damage of envelope components and the external and internal pressure fields is therefore essential. To this end, this research aims to develop an assessment framework that captures and quantifies the influence of dynamic envelope loss on internal and external aerodynamic loading.

## 2 CASE STUDY BUILDING

The building investigated in this study is a two-story structure located in Miami, USA, with open terrain exposure (Chuang and Spence, 2020). The main wind force-resisting system, illustrated in Figure 1, consists of four moment-resisting frames oriented along two perpendicular directions. The building envelope, configured as shown in Figure 2, comprises a total of 39 individual components.



**Figure 1:** Two-story two-bay structure (Chuang and Spence, 2020).



**Figure 2:** Building envelope system layout.

### 3 NUMERICAL MODELING

A numerical model using large-eddy simulation (LES) was established for the wind direction shown in Figure 1. The target mean wind profile follows the logarithmic law, expressed as:

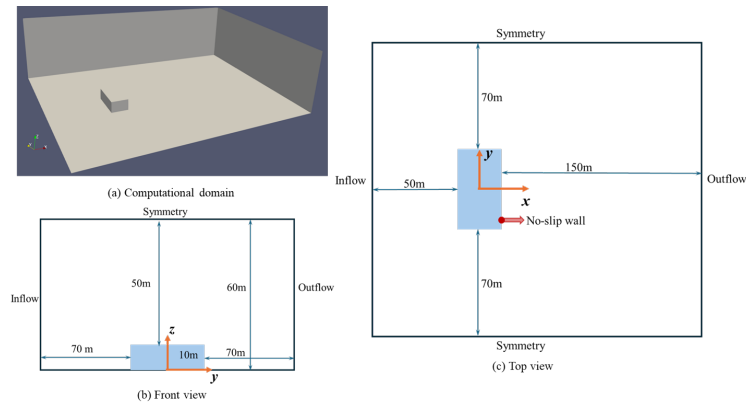
$$U = \frac{u^*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right) \quad (1)$$

where,  $z_0$  is the roughness length, taken as 0.03 m;  $\kappa$  is the von karman constant being 0.41; and  $u^*$  is the friction velocity.

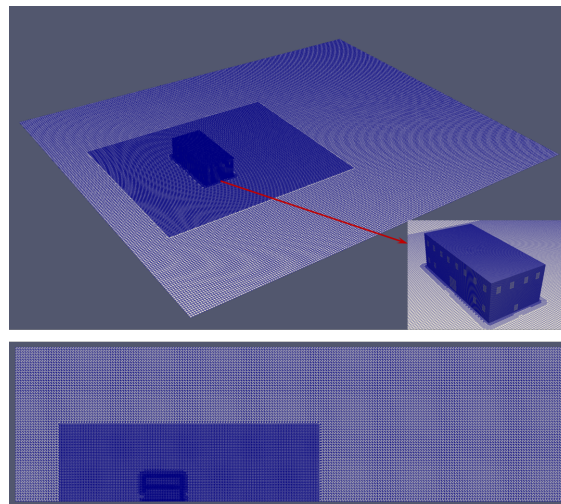
The LES is performed using the open source CFD tool OpenFOAM (Jasak et al., 2007). The computational domain is defined following best practices, as shown in Figure 3. The domain is discretized using a predominantly hexahedral mesh consisting of approximately five million cells. Refinement boxes are introduced to gradually increase the mesh resolution around the building, as shown in Figure 4. The inflow turbulence is generated using the digital filtering method incorporated in TINF (Wan et al., 2021). The wind is initially allowed to develop to a stable state, after which the envelope components gradually fail when the net pressure exceeds their specified pressure capacity.

### 4 PRELIMINARY RESULTS

In the LES framework, the building envelope is represented by baffle elements that are dynamically removed when net pressures exceed component-specific thresholds sampled from fragility functions. Preliminary results show that the framework effectively captures the dynamic evolution of internal and external pressure fields as envelope components are progressively lost. Velocity



**Figure 3:** Computational domain and boundary conditions: (a) Computational domain; (b) Front view; and (c) Top view.



**Figure 4:** Computational mesh.

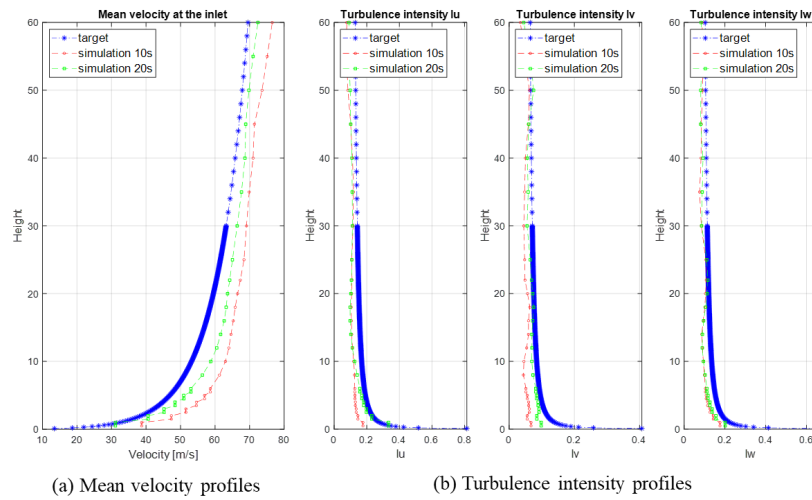
and turbulence intensity profiles (Figure 5) approach target values, consistent with the wind spectra observed in Figure 6. Comparisons with cases where external pressure is not updated based on damage demonstrate how the two-way coupling between progressive envelope loss and pressure evolution alters wind loading and building performance.

## 5 CONCLUSION

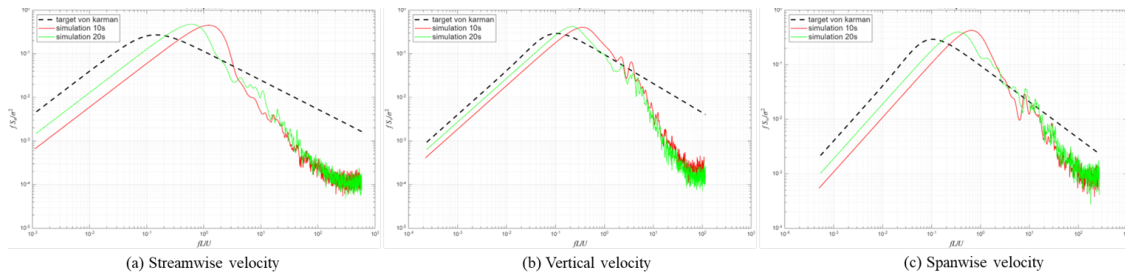
The developed LES framework captures the dynamic evolution of internal and external pressure fields as envelope components are progressively lost due to exceeding component-specific pressure thresholds. By modeling the building envelope with dynamically removed baffle elements, the approach quantifies how progressive envelope damage influences wind loading and overall building performance. Comparisons with cases that do not update external pressures based on damage highlight the significant impact of two-way coupling between envelope loss and aerodynamic loading.

## ACKNOWLEDGEMENTS

This work was supported in part by NSF Grants CMMI-2131111 and CMMI-2118488.



**Figure 5:** Comparison of: (a) mean velocity profiles; and (b) turbulence intensity profiles.



**Figure 6:** Comparison of wind spectra at: (a) streamwise direction; (b) vertical direction; and (c) spanwise direction.

## REFERENCES

- Sparks, P.R., Schiff, S., Reinhold, T., 1994. Wind damage to envelopes of houses and consequent insurance losses. *Journal of Wind Engineering and Industrial Aerodynamics*; 53(1–2):145–155.
- Kareem, A., 1985. Structural performance and wind speed-damage correlation in Hurricane Alicia. *Journal of Structural Engineering*; 111(12):2596–2610.
- Ouyang, Z., Spence, S.M.J., 2019. A performance-based damage estimation framework for the building envelope of wind-excited engineered structures. *Journal of Wind Engineering and Industrial Aerodynamics*; 186:139–154.
- Ouyang, Z., Spence, S.M.J., 2021. A performance-based wind engineering framework for engineered building systems subject to hurricanes. *Frontiers in Built Environment*; 7:720764.
- Wu, F., Gong, J., Xin, J., Zhou, J., Zhang, H., Zhao, N., 2024. Wind-induced damage estimation of envelope components for low-rise buildings: Incorporation of directionality and multiple openings. *Journal of Wind Engineering and Industrial Aerodynamics*; 246:105676.
- Chuang, W.C., Spence, S.M.J., 2020. Probabilistic performance assessment of inelastic wind-excited structures within the setting of distributed plasticity. *Structural Safety*; 84:101923.
- Jasak, H., Jemcov, A., Tukovic, Z., 2007. OpenFOAM: A C++ library for complex physics simulations. *International workshop on coupled methods in numerical dynamics*; 1000:1–20.
- Wan, J., Mackenzie-Helwein, P., 2021. Turbulence InflowTool. SimCenter.