Aerodynamic testing and response evaluation of a large-scale high-rise building model at a high Reynolds number

Aly Mousaad Aly [a], Suvash Chapain [b, *]

[a] WISE Research Lab, Louisiana State University, Baton Rouge, LA, USA, aly@lsu.edu
[b] WISE Research Lab, Louisiana State University, Baton Rouge, LA, USA, schapa3@lsu.edu

ABSTRACT
In this paper, experimental investigations of a large-scale (1:50) high-rise building model are performed at a high Reynolds number (~21 million), to evaluate the wind loads and the corresponding structural responses. A total of 256 pressure taps are mapped on all sides of the building model, to determine dimensionless pressure coefficients on the surfaces. Wind loads at each floor are evaluated using the pressure integration technique. The dynamic properties of the full-scale building are obtained from a finite element model in ANSYS. The wind-induced responses are calculated by applying wind loads on an equivalent lumped mass model of the building derived from the finite element model. Excessive vibration occurred in the cross-wind direction that exceeds the serviceability requirements. To attenuate these vibrations, a pendulum pounding tuned mass damper (PTMD) based on Hertz contact law is proposed.

Keywords: High-rise buildings; Open-Jet; Large-scale testing; Wind loads

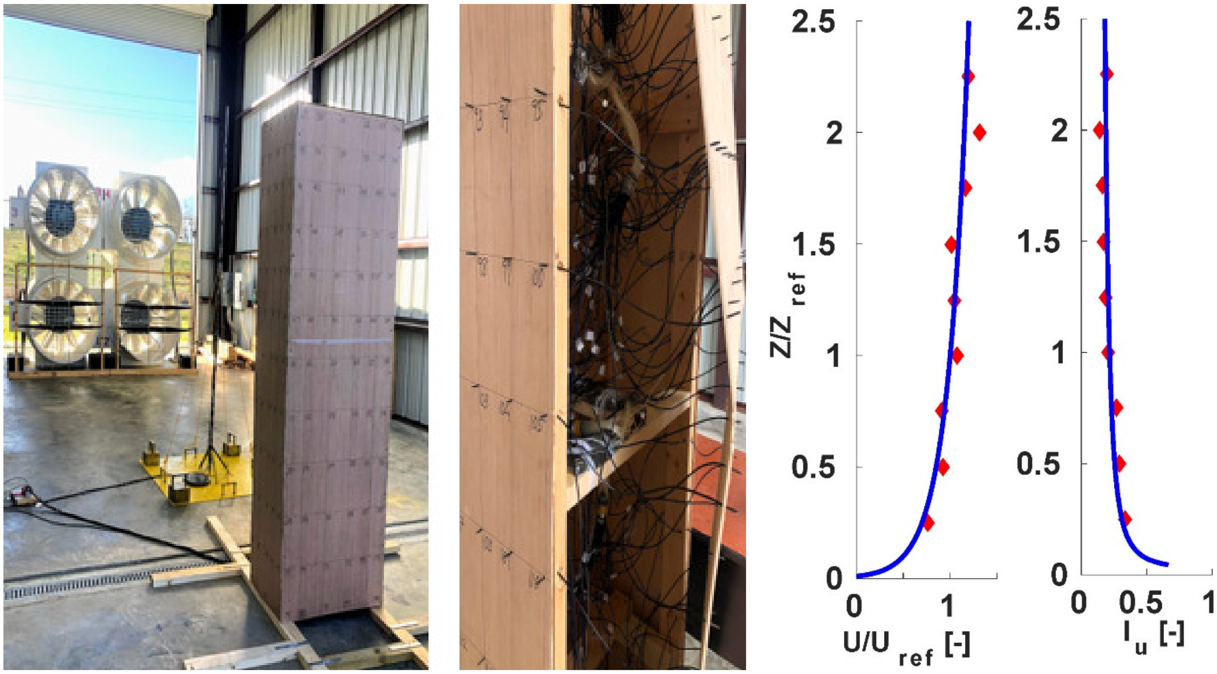
1. WIND LOADS ON TALL BUILDINGS

High-rise buildings are wind-sensitive structures, and usually, the lateral wind loads are a governing design factor. The pattern of wind flow around a building is distorted by the mean flow, flow separation, vortices formation, and wake development. These effects result in aerodynamic pressure on the structural system which imposes intense fluctuating forces on the facade and hence transferred to the main force resisting system with a potential to excite the whole building in the rectilinear directions and torsion. Crosswind responses can be significant for slender structures with low damping. Crosswind excitations are usually associated with “vortex shedding”. A high crosswind response can be induced if the vortex shedding frequency resonates with the natural frequency of the structure. Wind tunnel testing is fundamental for the accurate estimation of wind effects on tall buildings (Mendis et al., 2007).

1.1. Open-Jet Testing

Wind-tunnel tests are generally carried out in a turbulent flow on scaled models of the structure at relatively low Reynolds numbers, compared to the actual Reynolds numbers of the prototype structure. The choice of testing at a low Reynolds number is related to cost consideration and the limited availability of large wind tunnels. In this study, aerodynamic testing is performed in the modern open -jet facility at the Windstorm Impact, Science and Engineering (WISE) laboratory, Louisiana State University (LSU). This facility provides a realistic simulation of wind loads, by reducing the scaling effects (Aly and Yousef, 2021). The building model, and the wind velocity and turbulence intensity profiles are shown in **Figure 1**. The building is placed at twice the height of the open-jet and the base is restrained against overturning.

* Lead presenter



(a) (b)

Figure 1. Experimental setup: (a) aerodynamic test model and scanivalve pressure scanner arrangement inside it, and (b) along-wind normalized velocity profile and turbulence profile.

2. PRESSURE DISTRIBUTION

The time history of the wind forces at each story in the full scale is determined by scaling up the wind loads calculated using open-jet testing. The geometric scale of the model to prototype λ_L is 1:50. Assuming mean wind speed at 50 m in full scale to be 20 m/s and mean wind speed during open jet testing is 12.5 m/s.

This provides the velocity scale λ_V of 1:1.6. Based on that time scale becomes λ_T =1:31.25. Continuous-time series of pressure fluctuations were measured at a sampling frequency of 625 Hz using 256 taps installed in the building. The time history of dimensionless pressure coefficient is written as:

$$C_p(t) = \frac{P(t) - P_{ref}}{0.5 \rho U^2} \quad (1)$$

Where, $P(t)$, ρ, and $U$are pressure time history, air density, and mean wind speed measure at reference height (1m corresponding to 50 m at full scale). Wind loads at any story in a given direction can be obtained by integrating pressure over the tributary area corresponding to that story and expressed as:

$$F(t) = \int P(t)\, dA \quad (2)$$

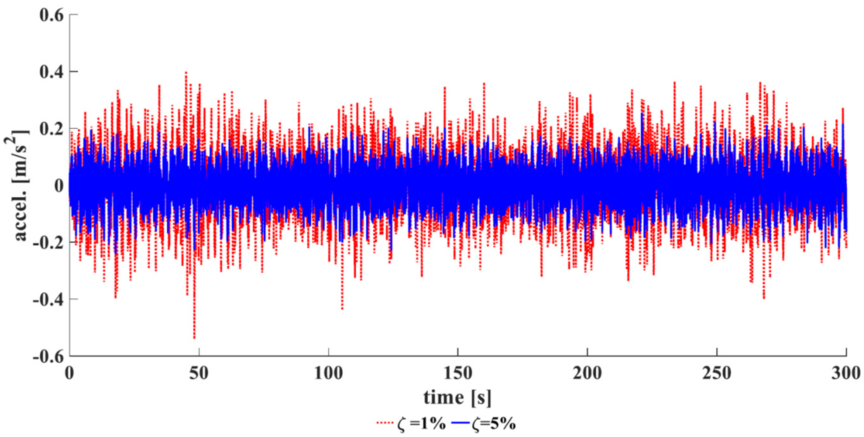


Figure 2. Controlled and uncontrolled acceleration response of floor 42.

2.1. Response Evaluation

Once the wind loads on each story are calculated using the pressure integration technique (Aly, 2013), the wind-induced responses in each direction are determined by solving the following equation of motion:

$$M\ddot{X} + C\dot{X} + KX = F(t) \tag{3}$$

where M, C, and K are the mass, damping, and stiffness matrix of the building. Since the pressure fluctuation in crosswind direction is relatively high, the crosswind responses of the building can be dominant over the along-wind response. **Figure 2.** shows the response of the building for two different values of damping (1% and 5%). To minimize the structural vibration in the crosswind direction, a pendulum pounding TMD is proposed. The pendulum PTMD has shown its effectiveness to mitigate vibrations (Chapain and Aly, 2021).

3. SUMMARY

A large-scale model of a high-rise building was tested to investigate its, in terms of aerodynamics and structural responses. The extensive hybrid experimental/computational framework enables the evaluation of the responses of tall buildings, under realistic wind simulation capabilities of open-jet testing. Excessive acceleration in crosswind direction exceeds the threshold of occupants' comfort. Performance-based design of a pendulum PTMD is proposed to attenuate excessive vibrations.

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