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Round-Robin Wind Tunnel Testing for High-Rise Buildings: Comparative Analysis of Approach Flow Effects on Aerodynamics and Structural Response

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SUMMARY:
Wind tunnel testing is fundamental to building design and standards development, requiring consistent results across facilities to ensure reliable structural performance predictions. Prior studies indicate that variations in experimental approach flows are a major source of differences in pressure measurements between wind tunnels, especially when other errors are controlled. To quantify the impact of approach flow variations on uncertainties in pressure measurements and structural response estimates, eight research and commercial laboratories are conducting a round-robin comparison study. This effort includes detailed measurement and analysis of approach flows and aerodynamic pressures on CAARC (Commonwealth Advisory Aeronautical Research Council) high-rise building models. Comparative results from participating laboratories will be presented, with implications for refining provisions on approach flows in wind tunnel testing standards and aligning them with uncertainty budgets for structural design. The study also provides datasets for consensus-based validation case studies, advancing Computational Wind Engineering (CWE) in structural wind engineering applications.
Keywords: Approach flow, CAARC building, Computational Wind Engineering (CWE), High-rise buildings, Structural response, Uncertainty, Urban environment, Wind tunnel testing.

1. INTRODUCTION

Wind tunnel testing remains a fundamental component of research and engineering practice in building aerodynamics, supplying critical data for structural design and building standard development. Consequently, consistent data quality across laboratories is essential for reliably predicting the structural performance of buildings under wind.

A previous study by the National Institute of Standards and Technology (NIST) compared low-rise building models across six wind tunnels and found variations in peak pressure coefficients and structural response of up to 40 % (Fritz et al. 2008). These differences stemmed from factors such as approach flow, instrumentation frequency response, reference pressure measurements, and model-to-integral length scale ratios. Similar investigations for high-rise buildings (Goliger and Milford 1988; Melbourne 1980) likewise identified approach flow variability as the dominant source of discrepancies, particularly when other experimental errors—such as transducer drift, calibration, and/or model geometry—were controlled within acceptable limits. The approach flow variability is expected to be even more influential under transient windstorms, including tornadoes and downbursts.

This research investigates the influence of atmospheric boundary layer (ABL) approach flow variations on aerodynamic pressure measurements and the resulting structural response estimates. Prior to conducting a round-robin comparison across multiple wind tunnel laboratories, confounding factors, such as measurement errors, are minimized to effectively isolate the role of approach flow.

The results of this round-robin study will strengthen wind tunnel testing standards, such as ASCE 49 (ASCE 2021), by ensuring compliance with allowable uncertainty budgets. They will also provide robust and detailed datasets for validating Computational Wind Engineering (CWE) simulations, facilitating consensus-based case studies and guidelines for accepting CWE-based wind loads for structural design of buildings. This contribution of experimental validation datasets for CWE directly addresses a priority research need identified at the ASCE workshop on *Advancements in Computational Wind Engineering* (Scott et al. 2023).

2. ROUND-ROBIN STUDY

This round-robin study involves nine research and commercial wind tunnel facilities to assess how variations in approach flow affect pressure measurements and the resulting building response estimates from structural analyses. The investigation focuses on differences in approach flow across laboratories and their propagation into building envelope pressures and pressure-derived structural response estimates for the CAARC (Commonwealth Advisory Aeronautical Research Council) high-rise building (Melbourne 1980), tested in both isolated and urban contexts.

The target approach flow is defined as a straight, atmospheric boundary layer (ABL) profile over suburban terrain, characterized by an aerodynamic roughness length z_0 = 0.3 m at full scale. The target wind speed at the building height (H = 180 m) is 45.3 m/s. Mean longitudinal wind speed and turbulence intensity profiles follow the Harris-Deaves model (Harris and Deaves 1980), as shown in Eqs. (1) and (2), respectively:

$$\bar{U}(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) + a_1\left(\frac{z}{z_g}\right) + \left(1 - \frac{a_1}{2}\right)\left(\frac{z}{z_g}\right)^2 - \frac{4}{3}\left(\frac{z}{z_g}\right)^3 + \frac{1}{4}\left(\frac{z}{z_g}\right)^4\right] \tag{1}$$

$$I_u(z) = \frac{2.63 u_* \eta \left[0.538 + 0.090 \ln(z/z_0)\right]^{\eta^{16}}}{\bar{U}(z)} \tag{2}$$

where u_* is the friction velocity, $\kappa = 0.4$ is the von Kármán constant, z_g is the gradient height, $a_1 = 5.75$, and η is a non-dimensional parameter defined as $\eta = 1 - (z/z_g)$.

Figure 1 illustrates the measurement locations of two three-dimensional velocity probes in empty domains, used to characterize the approach flow at the building site in the absence of the structure. Simultaneous measurements at the two locations were conducted to examine flow coherence and to determine integral time and length scales. The red circular markers indicate the locations of the fixed probe positioned at a height of 0.825*H*, while the blue circular markers indicate moving probes located on the plane passing through the building center, perpendicular to the flow direction.

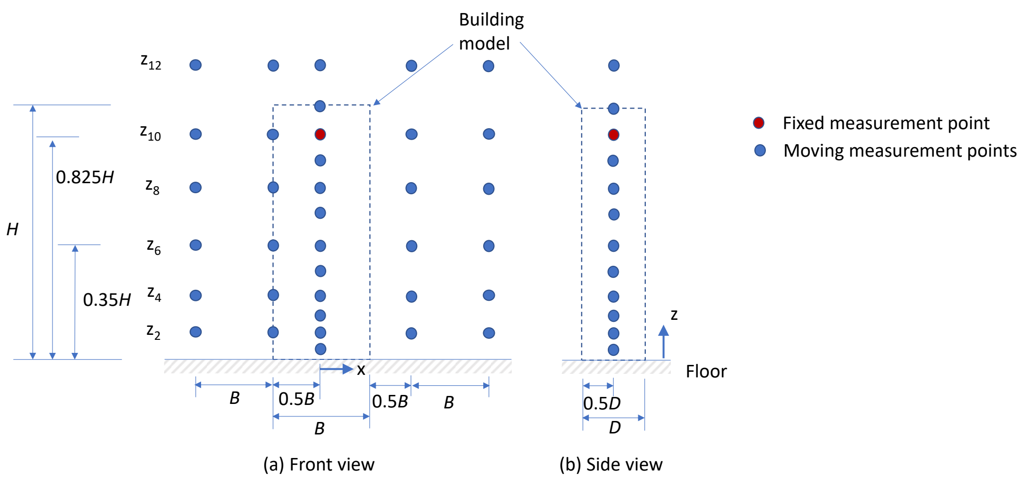

Figure 1. Measurement points for approach flow.

3. RESULTS

Comparative analysis is performed to examine variations in the characteristics of approach flows across laboratories and their impacts on building pressures, aerodynamic forces, and the propagation of these effects into structural behavior. Two cases are considered: (i) an isolated building and (ii) a building within an urban environment.

Figure 2 shows the spatial correlation distributions of the longitudinal (*u*), lateral (*v*), and vertical (*w*) velocity fluctuating components of the approach flow on a vertical plane perpendicular to the wind direction, relative to the reference location at $x = 0$ and $z = 0.825H$. These results were derived from a laboratory's dataset measured using the anemometer array positioned as shown in Figure 1. The color scale represents the degree of correlation relative to the reference location, and the dashed lines indicate the target position of the building model (measurements are carried out in empty tunnel conditions). As observed in Figure 2, high correlation of the streamwise velocity fluctuation component (*u*) extends both horizontally and vertically from the reference point, producing largely coherent along-wind fluctuating aerodynamic loads to act on the windward envelope of the building. In contrast, the correlations of the spanwise (*v*) and vertical (*w*) velocity fluctuating components are spatially more confined, potentially leading to substantial variations in across-wind fluctuating aerodynamic loads. This suggests that the across-wind response of the building is likely more sensitive to approach flow variations than its along-wind response.

At present, we are continuing to examine deviations in approach flow characteristics and their effects on building pressures and aerodynamic forces, and, ultimately, on its resulting structural response estimates. Additional results will be presented during the conference.

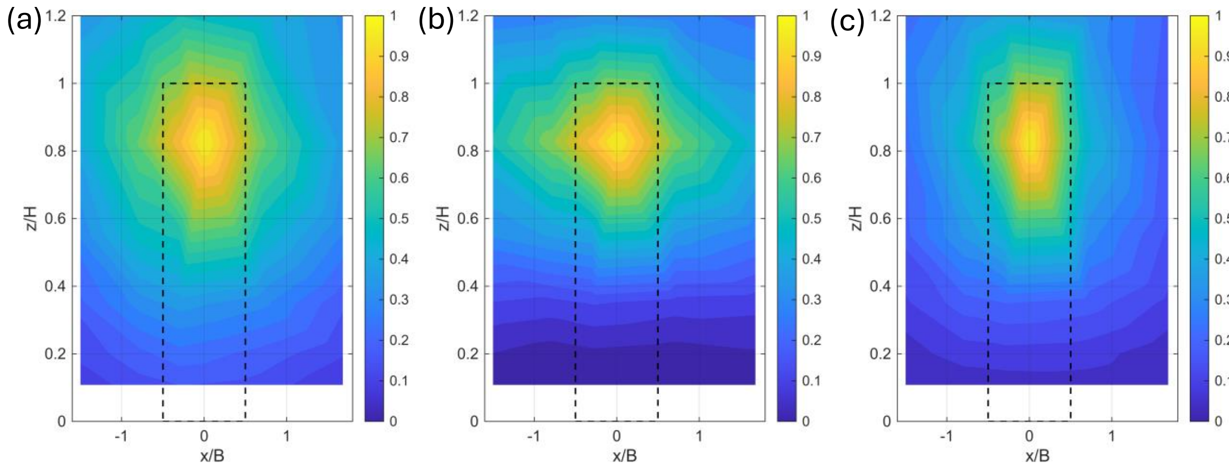

Figure 2. Spatial distribution of correlation coefficients for fluctuating velocity components: (a) along-wind (*u*), (b) lateral (*v*), and (c) vertical (*w*).

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