ABSTRACT

Wind tunnels are essential for studying wind loads on structures, with larger experimental facilities allowing assessment of wind effects at greater scales, offering higher Reynolds numbers and improved spatial and temporal resolution of local pressure measurements. However, at larger simulation scales, Boundary Layer Wind Tunnel (BLWT) experiments often struggle to replicate the large-scale turbulent (LST) gust structures present in the atmospheric boundary layer (ABL), making it difficult to generate integral length scales in the wind tunnel that match full-scale conditions, and that are known to play a critical role in the development of extreme wind pressures on building structures. This research aimed to study the impact of LST effects on wind loads for low-rise buildings through active generation of large-scale gusts in the BLWT. The study applied a multi-staged flow conditioning techniques to achieve higher integral length scales across several turbulence levels, enabling more accurate predictions of wind load effects and ultimately contributing to enhancing wind hazard resilience of civil infrastructure. Experiments were conducted at the University of Florida (UF) self-configuring BLWT.

Initial BLWT experiments comprised an investigation into the modulation of large-scale turbulence using a multi-fan flow control system known as the Flow Field Modulator (FFM) consisting of 319 fans. The FFM operated in conjunction a mechanized roughness (Terraformer) grid to achieve target integral length scales and turbulent levels at the BLWT test section. The FFM system was responsible for generating low-frequency turbulent gust structures, while the roughness grid was used to impart mechanical turbulence (i.e., small-scale turbulent eddies) into the flow. Both systems were controlled by a Governing Convergence Algorithm (GCA), which automatically calibrated wind tunnel settings based on anemometric measurements to achieve the desired (i.e., target) turbulence conditions at the BLWT testing section. The combined flow conditioning systems (FFM and Terraformer) allowed precise simulation of turbulence intensity (I_u) for different terrain and enabled longitudinal integral length scale (L_u^x) approximately 20 times larger than LST conditions achieved through traditional BLWT approaches (i.e., no active turbulence generation) for the same geometric scale.

Following the initial series of flow calibration experiments, a series of aerodynamic BLWT tests were carried out on a 1:20 scale model of the Wind Engineering Research Field Laboratory (WERFL) low-rise building to evaluate the effects LST on local wind pressures on the surface of the building model. The turbulence levels (I_u) were varied between 15% and 30%, while the longitudinal integral length scale (L_u^x/H) was modulated between 5 and 40 to study suction pressure and correlations across the building's roof, focusing mainly on areas near the roof edges and corners where flow separation occurs. Further analysis has been performed to apply and evaluate the Partial Turbulence Simulation (PTS) method and assess the effects of small-scale energy mismatches (ΔES) on the PTS-predicted peak pressures compared to the modulated full-scale peak pressures.

The results of this thesis demonstrate that the multi-fan system significantly increased the longitudinal integral length scale (L_u^x) compared to baseline wind tunnel conditions, effectively simulating large-scale turbulent structures. Under high turbulence intensity $(I_u = 0.3)$, the magnitude of negative mean pressure coefficients decreased as L_u^x/H increased, particularly when the wind azimuth was aligned with the building's longest dimension. Additionally, larger turbulent length scales led to higher local peak pressures, especially in oblique wind directions ($\theta = 45°$), and amplified non-Gaussian behavior in high suction zones. The study also validated the Partial Turbulence Simulation (PTS) method, confirming its accuracy in predicting peak pressures under various turbulence conditions, particularly in critical areas like roof corners and edges. Slight mismatches between conical vortices and near leading edges were linked to small-scale turbulence energy discrepancies (ΔES). As this energy mismatch decreased, the differences between the PTS-predicted and full-scale prototype peak pressures diminished, further reinforcing the reliability of the PTS method for predicting wind pressures in key areas.

The implications of this thesis extend to informing future building codes, such as ASCE 7, by providing crucial insights into wind loads on low-rise buildings, particularly for components and cladding (C&C). It highlights how advanced flow conditioning techniques in wind tunnels can improve the simulation of atmospheric turbulence, ultimately leading to enhanced experimental techniques to improve building performance in strong winds.