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Characterization and time–frequency analysis of the flow around rectangular bluff bodies in downburst-like winds

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SUMMARY:
This study investigates the aerodynamic effects on rectangular bluff bodies exposed to downburst-like impinging jets, both in isolation and superimposed on an Atmospheric Boundary Layer (ABL). Time–frequency and spatial coherence analyses of pressure and velocity fields are employed to characterize the transient flow dynamics and to identify dominant unsteady flow mechanisms. The ultimate objective is to improve the physical understanding and modelling of wind loads acting on civil structures subjected to downburst-like wind events. Five representative bluff-body configurations are examined: a horizontally extruded 5:1 rectangular cylinder (BARC), two high-rise rectangular buildings (CAARC) of different scales, and two Low-Rise rectangular Buildings (LRB) at different scales. Experiments provide time-resolved surface pressure measurements and velocity data in the incoming flow and wake regions. The temporal evolution of characteristic flow frequencies and the spatial coherence of pressure fluctuations are analysed. Particular attention is devoted to the role of building height through a comparative analysis between low-rise and high-rise configurations. In addition, the effects induced by the superposition of an ABL on the impinging jet are assessed, with emphasis on the resulting modifications of the flow field around and downstream of high-rise buildings.

Keywords: Downburst-like experimental flows, atmospheric boundary layer, rectangular bluff bodies, pressure data, Particle Image Velocimetry, time–frequency analysis

1. INTRODUCTION

Downbursts are intense, short-duration downdrafts generated within convective storms that accelerate toward the ground and spread radially upon surface impingement, producing highly transient and spatially non-uniform near-surface wind fields (Fujita, 1985). Peak wind speeds may locally exceed 30–50 m/s, posing a significant threat to buildings and infrastructure (see, e.g., Holmes and Oliver, 2000). The associated flow field typically exhibits a nose-shaped horizontal velocity profile close to the ground and the formation of a large-scale vortex structure beneath the parent cloud, often described as vortex-ring-like in nature (Proctor, 1988). Owing to their short duration, limited spatial extent, and pronounced three-dimensionality, downbursts are challenging to investigate using field measurements alone (Hjelmfelt, 1988). As a result, laboratory experiments based on downburst-like impinging jets have been widely adopted to reproduce the dominant kinematic features of downbursts under controlled and repeatable conditions. Although impinging-jet experiments cannot capture the full thermodynamic complexity of real downburst events, they have been shown to reproduce the key characteristics of the near-surface radial outflow and the associated large-scale unsteady structures that are most relevant for wind-engineering applications. Large-scale experimental campaigns conducted at the WindEEE Dome have demonstrated that transient impinging jets operating at Reynolds numbers of order 10^6 reproduce the spatio-temporal evolution of near-surface outflows with reasonable agreement with full-scale observations (Canepa et al., 2022b). The capability to superimpose an atmospheric boundary layer onto downburst-like flows has further enabled investigations under conditions that are more representative of realistic atmospheric exposure (Canepa et al., 2022a; Hangan et al., 2017; Kodakkal et al., 2025). Previous studies have reported significantly amplified pressure fluctuations and aerodynamic loads on structures subjected to downburst-induced winds compared to conventional ABL flows (Chen and Letchford, 2004; Jesson et al., 2015). Similar load amplification and marked departures from quasi-steady aerodynamic behaviour have also been observed for square and rectangular cylinders subjected to accelerating inflow conditions, highlighting the importance of flow unsteadiness in governing the aerodynamic response (Brusco et al., 2024; Lunghi et al., 2024; Morello et al., 2025). Despite these advances, while the aerodynamic loading induced by transient wind phenomena has been extensively investigated, comparatively limited attention has been devoted to the underlying unsteady flow organisation and the associated coherence properties of pressure fluctuations. In downburst-like flows, turbulence is primarily generated by rapid flow acceleration, radial spreading, and strong transient shear associated with large-scale vortical structures and near-ground interaction, rather than by the shear-driven mechanisms typical of synoptic boundary-layer winds (Sengupta and Sarkar, 2008). As a consequence, coherence models developed for stationary ABL flows may not be directly applicable to downburst-induced loading (Brusco et al., 2024). Motivated by this gap, the present study focuses on the spatial and temporal coherence of unsteady pressure fluctuations acting on rectangular bluff bodies exposed to downburst-like impinging jets, with and without the effects induced by the superposition of an ABL flow. Experiments provide time-resolved surface pressure measurements and velocity data in the incoming flow and wake regions. The temporal evolution of characteristic flow frequencies and the spatial coherence of pressure fluctuations are analysed using wavelet based time-frequancy analysis. Particular attention is devoted to the role of building height through a comparative analysis between low-rise and high-rise configurations.

2. METHODOLOGY

The investigation considers five bluff-body geometries selected to assess the influence of structural geometry and aspect ratio in downburst-like wind conditions (Fig. 1). These include: (i) a horizontally extruded 5:1 rectangular cylinder (BARC); (ii) two high-rise rectangular buildings (CAARC) at different scales; and (iii) two low-rise rectangular buildings (LRB) at dif-

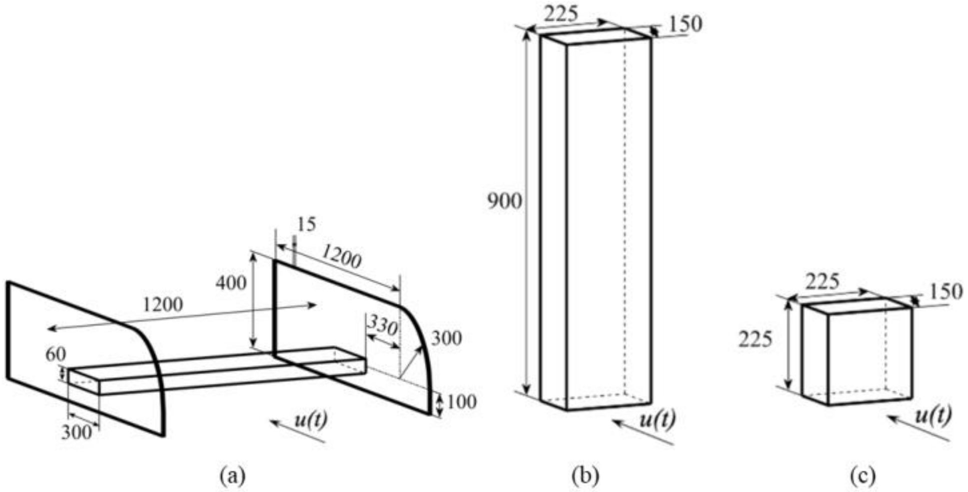
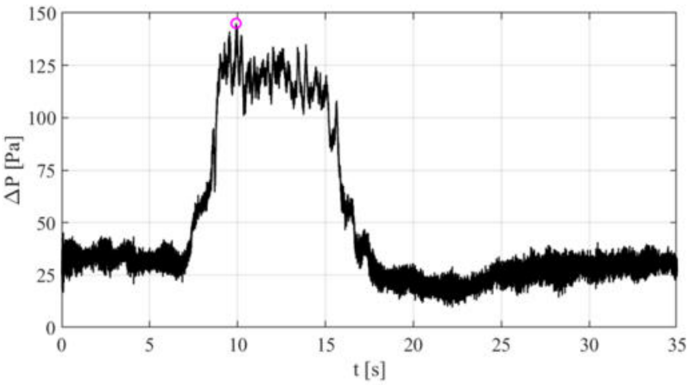


Figure 1. Sketches of: (a) horizontally extruded 5:1 rectangular cylinder; (b) high-rise buildings (CAARC); and (c) low-rise buildings (LRB). All dimensions are given in millimetres. The sketches are not in scale.

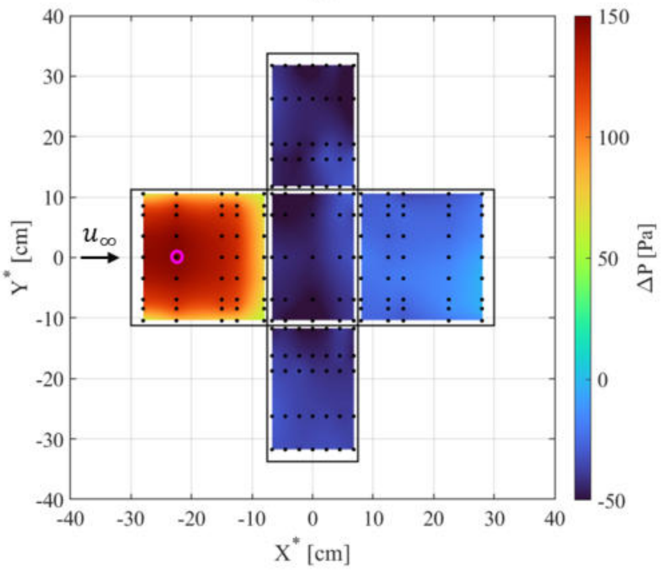
ferent scales. The comprehensive characterisation of downburst-like flows, both in isolation and when superimposed on an atmospheric boundary layer, has required the measurement of the incident flow field features together with the unsteady aerodynamic pressure distributions. To this end, time-resolved three-component velocity measurements in the incoming flow and selected wake regions are obtained using multi-hole pressure probes (Cobra probes). Unsteady surface pressures are acquired through distributed pressure taps connected to high-frequency pressure transducers, enabling detailed analysis of pressure fluctuations, spectral content, and spatial coherence. Particle Image Velocimetry (PIV) measurements are conducted to evaluate instantaneous flow fields and to identify coherent flow structures and their temporal evolution.

3. RESULTS AND DISCUSSION

Figure 2 shows a representative example of the unsteady pressure response measured on the surface of the LRB under combined downburst-like and ABL flow conditions. Figure 2a reports the ensemble-averaged pressure time history, obtained from eight realisations of the same experiment. The pressure signal is defined as the difference between the measured surface pressure and a reference static pressure. A pronounced transient increase is observed following the arrival of the downburst-induced flow at the model location, followed by a gradual decrease



(a)



(b)

Figure 2. Example of unsteady pressure response measured on the low-rise rectangular building under combined downburst-like and ABL flow conditions.

as the flow evolves and weakens. The peak pressure occurs during the phase characterised by the primary outflow region of the downburst. The high level of pressure fluctuations observed during this interval reflects the strongly non-stationary nature of the aerodynamic loading experienced by the LRB during this event, unlike conventional ABL conditions. Figure 2b presents the instantaneous surface pressure distribution at the time T=10s (highlighted by the magenta marker in Fig. 2a). The spatial distribution reveals significant pressure gradients across the model surfaces, consistent with the combined effects of transient flow impingement, local acceleration, and unsteady flow separation.

4. CONCLUSIONS

Experimental results on the unsteady pressure response of rectangular bluff bodies exposed to combined downburst-like and ABL flow conditions will be presented at the Conference. The findings provide qualitative insight into the characteristics of downburst-induced pressure distributions on different structures, highlighting the strongly non-stationary nature of the associated aerodynamic loads and field distributions. We will focus on systematic time-frequency investigations of pressure spectra, the temporal evolution of dominant frequencies, and spatial coherence along the surfaces of the investigated bodies, as well as on their dependence on flow conditions. The phenomenological discussion will be enriched through PIV measurements, enabling direct correlation between unsteady surface pressure fields and the underlying flow structures. These combined analyses are expected to support a more quantitative and physically consistent interpretation of unsteady aerodynamic loading mechanisms associated with downburst–ABL interaction.

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