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Aerodynamic forces on the roofs of low-, mid- and high-rise buildings subject to transient winds

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ABSTRACT

Transient winds, such as thunderstorm downbursts, are the cause of design-load wind speeds in many countries. An understanding of the loading experienced by buildings during a downburst is therefore important to allow well designed and engineered buildings to be constructed. In contrast to boundary layer winds, the maximum wind speed in thunderstorm downbursts occurs as low as $z_m = 30$ m above the ground, within the range of heights of man-made structures, suggesting that the wind loading will be dependent on the building eaves height relative to z_m. In a novel set of experiments, the University of Birmingham Transient Wind Simulator (a 1 m diameter impinging jet with aperture control) has been used to simulate a downburst striking buildings of different heights, ranging from below to above z_m. Two forms of building have been used – a square-plan, flat-roofed structure, and a rectangular, portal-frame – at three angles (0°, 45° and 90°) relative to the radial wind direction. Pressure coefficients have been calculated (using eaves height velocity) over the roofs of these buildings, and are shown to be of greatest magnitude when the roof is above the region of maximum outflow velocity, with the exception of windward edges perpendicular to the flow, when they are generally greatest for the lowest building heights.

1. Introduction

Convection in thunderstorm cells can lead to the development of tornadoes or thunderstorm downbursts, i.e., transient wind events which have a short duration but which produce high wind speeds. These speeds are the building design wind speeds in many parts of the world (Chay and Letchford, 2002a).

Downbursts are formed when upward air currents in the convection region of a thunderstorm cool rapidly due to the evaporation of precipitation (Wakimoto and Bringi, 1988). The cooled air is denser than the surrounding air and falls to the ground, with a ring vortex forming (see Vermeire et al (2011) for details). This vortex is carried outwards with the radial outflow which forms when the downdraft impinges on the ground (Fujita, 1981), leading to high wind speeds in the near ground region. In contrast to the monotonically increasing vertical profiles of velocity in ABL flow, the maximum velocity in a downburst outflow occurs at a height $z_m = 30$–100 m above the ground (Fujita and Wakimoto, 1981; Hjelmfelt, 1988).

The most intense downbursts, termed microbursts by Fujita (1981), have a diameter of only ~1000 m and a lifetime of ~5 min (Fujita, 1981; Holmes et al. 2008) and consequently are difficult to measure at full-scale. Despite efforts such as the NIMROD and JAWS projects (Fujita, 1981), and (more recently) the Thunderstorm Outflow Experiment (Gast and Schroeder, 2003; Holmes et al. 2008), only a small number of full-scale downbursts have been measured, providing a limited data set to aid the understanding of these events. When considering wind loading on structures, the unpredictability of where and when a downburst will strike makes it very difficult to obtain full-scale pressure measurements over a structure – the chances of a single, instrumented building being subject to a downburst are extremely small. Lombardo (2009) has, however, successfully identified a small number of downburst events from historical velocity data recorded at the Texas Tech University Wind Engineering Field Research Laboratory (WERFL), and examined the corresponding pressure data from tappings over the WERFL building (a 9 m × 14 m × 4 m tall, rectangular plan building).

Notwithstanding Lombardo's success in measuring data at full-scale, the physical simulation of downbursts in engineering laboratories is essential in order to understand their impact on structures of different types and proportions. A variety of methods have been used to physically simulate downbursts: very small-scale density driven flows (e.g. Lundgren et al. 1992); slot jets (e.g. Butler

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and Kareem, 2007; Lin et al. 2007); multi-fan wind tunnels (e.g. Butler et al. 2010); steady impinging jets (e.g. Chay and Letchford, 2002a, 2002b; Choi, 2004; Wood et al. 2001; Zhang et al. 2014, 2013 and pulsed impinging jets (e.g. Haines et al. 2013; Jesson et al. 2015; Mason, 2003; Mason et al. 2009a; McConville et al. 2009). As has been discussed by Vermeire et al. (2011), who compared numerical simulations of impinging jets and cooling source downbursts, fan-driven impinging jets do not have the same forcing mechanism as a full-scale downburst and so do not provide a full simulation of a downburst despite the creation of a ring vortex. Having examined the data presented by Vermeire et al. (2011), the authors believe that, at the time and location of maximum radial velocity, the pulsed impinging jet facility used by Jesson et al. (2015) is a reasonable approximation to the flow field of a downburst. As such, the simulations performed at this facility, the University of Birmingham Transient Wind Simulator (UoB-TWS), constitute a partial simulation which may be used to investigate the transient pressure field on a structure as the ring vortex passes over it. The UoB-TWS was used for the work presented in this paper, and it is described in Section 2.1.

The distinction between low- and high-rise buildings is particularly important in the context of downbursts, due to the closeness of z_m to the ground. In the context of atmospheric boundary layer (ABL) winds, low-rise buildings have been defined as those with width greater than twice the height, h, and $h<30$ m (Uematsu and Isyumov, 1999). When discussing downbursts, a natural definition of low- and high-rise is that the eaves height of a low-rise structure is below z_m while that of a high-rise structure is above; in the context of this study, this definition is consistent with that for ABL flow. Although a number of the aforementioned studies have measured the pressure field over building models (e.g. Chay and Letchford, 2002a, 2002b; Jesson et al. 2015; Mason et al. 2009a; Sengupta et al. 2008; Sengupta and Sarkar, 2008), the small length scale ($\sim$1:1600 in the case of Jesson et al. 2015) and value of z_m of these simulations means that these buildings are high-rise structures under this definition. The pressure field on the walls of prismatic, low-rise buildings subject to a simulated transient gust front has been measured by Butler et al. (2010), using a multi-fan, variable speed wind tunnel to simulate a rapid increase in velocity. No pressure measurements were made on the model roofs by Butler et al., and their work may be limited by not simulating the vortex-driven nature of the downburst flow field-turbulence intensity is known to affect flow separation around bluff bodies (Jensen, cited by Melbourne (1993), Holmes (2001)) and hence not recreating the vorticity field of a downburst may affect the pressures measured. The work described in this paper extends the work of Jesson et al. (2015) to a range of building heights, from low- to high-rise, allowing the effect of building height relative to z_m to be determined.

This paper presents the findings of a research project aimed at quantifying the pressure field on low-, mid- and high-rise structures in transient, downburst winds, and how the field varies with building height. It extends the work of Jesson et al. (2015) by varying the height of the model buildings subjected to a simulated downburst-type wind. In doing so, the variation of the pressure field due to the building eaves height relative to z_m is measured, and the pressure field due to a downburst elucidated for both low- and high-rise buildings. Following this introduction, the UoB-TWS, the experimental facility used to gather the data presented in this paper, is described in Section 2. The pressure and force coefficients measured over building models with a range of heights spanning low- to high-rise, subject to a simulated thunderstorm downburst, are presented and discussed in Section 3. Section 4 summarises the important conclusions drawn from the work.

2. Experimental setup

2.1. University of Birmingham Transient Wind Simulator (UoB-TWS) facility

The UoB-TWS, originally developed by McConville et al. (2009), is an impinging jet facility with a vertical, circular, downward jet of diameter $D=1$ m. It has subsequently been improved and in its current incarnation uses nine 0.85 m^2 cross-section axial flow fans to direct air into a settling chamber which, in turn, feeds a circular nozzle, the exit of which is controlled by a set of eight flaps. The opening of these flaps is controlled by the same computer and software which controls the fan speed in order to make the experimental runs as repeatable as possible. In this way, rapidly accelerating downward flow is created which causes the formation of an entrainment vortex at the interface between the jet and the surrounding air. When the jet impinges on the ground plane, this ring vortex travels with the outflow. The jet velocity (V_j), measured immediately below the nozzle exit, has a mean value of 13.1 m s^{-1} (with negligible variation over the central 90% of the diameter (McConville, 2008)), and a turbulence intensity of 13%. In order to permit instruments to be installed as closely as possible to the downburst (to, for example, minimise tube lengths to pressure tappings), the jet impinges onto a raised ground plane (Fig. 1).

More detail of the UoB-TWS may be found in McConville et al. (2009) and Jesson et al. (2015).

2.2. Simulated flow field

Previous work has shown that the scales of the physical simulations may be estimated as 1:1600, 1:2.6 and 1:600 for length, velocity and time, respectively. Using these scales gives a good match to full-scale data (Fig. 2 and Jesson et al (2015)), with the simulation data showing the peak velocity and the initial rapid acceleration of a full-scale event; the full-scale data is from the Andrews Air Force Base (AAFB) event, described by Fujita (1985). The velocity measurements were made at a range of radial distances, r, from the centre of the downdraught, with $r/D=1.0$, 1.25, 1.5, 1.75, 2.0 and 2.5, at 10 mm (16 m full-scale) vertical increments spanning 0.01–0.25 m (16–400 m full-scale) from the ground plane (Jesson et al. 2015). A ten-run, ensemble-mean approach was used (following McConville et al (2009)) to allow generic features of downbursts to be examined in isolation from the run-to-run variation which is a feature of both full-scale downbursts (for example, Choi, 2004; Hjelmfelt, 1988; Lombardo, 2009) and UoB-TWS runs. A fifty-point moving average

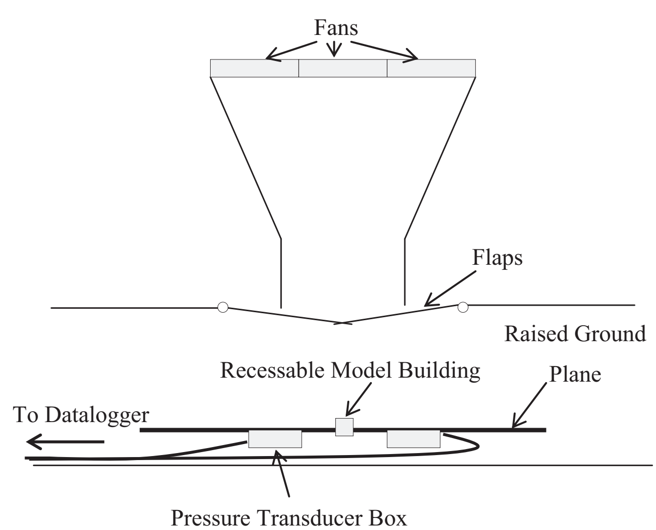

Fig. 1. A schematic of the UoB-TWS facility (Jesson et al. 2015).