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Comparison of microburst-wind loads on low-rise structures of various geometric shapes

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ABSTRACT

Microburst can produce downdraft and strong divergent outflow wind, whose characteristics are distinct from the atmospheric boundary layer (ABL) wind. In the present study, microburst-wind loading effects on low-rise structures – a cubic-shaped building, a grain bin and two gable-roofed buildings – are evaluated and compared by performing laboratory tests on scaled models using a microburst simulator at Iowa State University. Velocity and turbulence intensity profiles at selected locations were studied. The distribution of mean and root-mean-square pressure coefficients for the models are shown for selected cases and compared with those obtained in the ABL wind. Results suggest that wind loads change significantly as the radial location, orientation and geometric shape of the structures vary. It was observed that at or near the center of the microburst, high external pressures occur for all structures, resulting in a large downward force on the roof. In the outburst region, the distribution of pressure coefficients on the structure envelope was found to be similar to those in the ABL wind, although actual wind load magnitudes may be much larger in the microburst wind. Different roof slopes and its cross-section resulted in different pressure distribution and overall wind loads on the models located in the outburst region. The low-angle gable roof and conical-shaped roof experience lower drag but larger uplift in the outburst region compared to buildings with flat roof and high-angle gable roof. The geometric parameters of the roof did not influence the wind loads at or near the center of the microburst where high positive static pressures govern the wind loads. Finally, it is found that the effect of geometric scale of a model on the mean wind loads in the outburst region is minor when it is within a blockage ratio of 3% as tested in the present study.

1. Introduction

A microburst is a small-size and intense downdraft that impinges on the ground resulting in a divergent outburst wind with the radial extent being less than 4.0 km (Fujita, 1985). This damaging outburst wind can sometimes reach up to 168 mph (NOAA Website, 2010) with the maximum velocity very close to the ground surface. The flow field of a developed microburst is significantly different from that of the conventional atmospheric boundary layer (ABL) wind. Statistical summarization of the meteorological studies suggests that the flow field of a microburst at its maximum-wind producing status shares many similarities with the laboratory impinging jet flow (Hjelmfelt, 1988). Besides the wall-jet-like outburst flow, the microburst also produces high static pressure in the core and large turbulence in the divergent outflow. Because of these unique flow features, the microburst wind could be potentially dangerous to civil structures which are normally designed to resist the conventional ABL wind.

Low-rise structures, such as houses, grain bin or silos, industrial buildings and warehouses, etc., are common in rural and suburban areas of the United States. Low-rise buildings are particularly more vulnerable to extreme wind loads than engineered structures. Over past few decades, many studies have been conducted to investigate wind loading effects on various types of low-rise structures, through either wind tunnel tests or full-scale field studies. A limited number of citations are referred here because their data are used here for comparison (Castro and Robins, 1977; Cook and Redfearn, 1980; MacDonald et al., 1988). Due to the strong near-ground wind and unique flow characteristics, microburst winds are supposed to have distinct wind loading effects on low-rise structures. Current building codes and standards do not provide provision for estimation of wing loads of structures in a microburst for wind loads. Therefore, a better understanding of the microburst-wind loading effects is warranted, particularly in thunderstorm-prone areas. To date, several studies have been conducted to assess the microburst wind loads on cubic-shaped buildings. Nicholls et al. (1993) studied the flow structures around

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a cube-shaped house model in microburst-like winds. Chay and Letchford (2002) investigated the pressure distribution over a cube induced by a simulated microburst wind in a laboratory study. Sengupta and Sarkar (2008) conducted an experimental study to quantify the transient loads acting on a cube with an impinging-jet-based translating microburst simulator. Since the total number of related research is very limited, a lot of work is still needed to quantify the microburst-induced wind loads on different structures.

In the present study, the microburst wind loading effects on a set of low-rise building models have been investigated. The microburst wind was simulated by using a steady-impinging jet in WiST (Wind Simulation and Testing) Laboratory of the Department of Aerospace Engineering at Iowa State University. A steady impinging jet flow was used to simulate a steady microburst-like phenomenon which replicates the wind speed profile when the maximum wind is produced during the evolution of a microburst while ignoring the time-domain evolution of the microburst flow field. The models that were studied include a cubic-shaped building, a conical-roofed grain bin, and two gable-roofed buildings with different roof slopes but same plan dimensions. The purpose of this study was to establish the initial database of microburst wind loads for basic low-rise structures. By exploring the uniqueness and characteristics of the microburst wind loading, the authors hope that the results of the present study may help improve the wind loading design of the low-rise structures in thunderstorm-prone areas.

2. Experimental setup

Fig. 1 shows the steady impinging-jet flow simulator in the WiST Lab at Iowa State University and its schematic view, which was used in the present study. The jet flow is produced constantly by a fan on the top and impinges on a wooden ground plane to form a steady wall-jet flow field. The diameter of the nozzle (D) is about 0.6 m (2 feet). The geometric scale of the flow field was calculated as ~1:650 if compared to a small-sized microburst event with a diameter of 400 m (range 400–4000 m). The distance between the nozzle exit and the ground plane (H) was set to be 2 diameters of the nozzle ($H/D=2$). A honeycomb and several screens are placed at the exit of the nozzle to produce uniform velocity across the exit and reduce the turbulence of the issuing jet (approximately 2%). Velocity was measured using a Cobra probe (a multi-hole pressure probe, TFI Pvt. Ltd.®), which has the ability to measure all three velocity components simultaneously. The velocity data were sampled for 30 s at a sampling frequency of 1250 Hz at each measurement point, where the measurement uncertainty of the Cobra probe was within ±0.5 m/s. The flow velocity at the nozzle exit of the ISU microburst simulator was set to 13 m/s (i.e., $V_{jet} \approx 13$ m/s). The corresponding Reynolds number of the flow was 5.2×10^5 based on the diameter of the jet nozzle. In Zhang et al. (2013), the velocity profile generated by this simulator was compared with existing data from the field and laboratory studies and reasonable agreement was found. Therefore, this steady impinging jet has proven to be a valid model for laboratory studies.

Fig. 2 presents the geometry of low-rise structural models used in the present study. All of these models were precisely fabricated using a 3D rapid prototyping machine located in the WiST Lab. To compare the effects of different roof shapes, the mean roof height of the grain bin model was kept the same as that of the gable-roofed models. Dimensions of all models and number of pressure taps are listed in Table 1. According to the geometric scale of 1:650 used here, the models studied represent large low-rise buildings like industrial buildings or warehouses instead of residential buildings. It is suggested that a larger microburst simulator be used in the future to test models with a larger geometric scale than used here to determine any scaling effects. The effects of scaling based on limited test cases are discussed later in this paper.

Pressure taps were uniformly distributed over these four models (see Table 1 for number of taps). These pressure taps were connected to DSA3217 pressure scanners (Digital Sensor Array, Scanivalve Corp.®) using tygon tubing (1.5 mm in diameter and 0.3 m long) for the surface pressure data acquisition. The pressure data were averaged over 10,000 data points collected with a frequency of 100 Hz. Since the tubing is trimmed equally short and no restrictors were included in the entire pressure acquisition system, the magnitude and phase distortion of the pressure fluctuation were insignificant (Irwin et al., 1979) and hence neglected in the present study. Both the velocity and pressure measurements were taken at five radial locations within the flow field, namely $r/D=0.0$, 0.5, 1.0, 1.5, and 2.0 as shown in Fig. 1. Resultant wind loads were also measured using a highly-sensitive force-moment sensor (JR3, model 30E12A-I40). The JR3 load cell is capable of measuring forces in three directions and the bending moment or torque about each axis. For each test run, 15,000 data points were taken with a sampling frequency of 1000 Hz. The measurement uncertainty of the sensor is ±0.25% of the full range (40 N).

3. Results and discussion

3.1. Velocity and turbulence intensity

The flow field of the steady impinging jet generally has greater complexity than the conventional ABL wind. The characteristics of

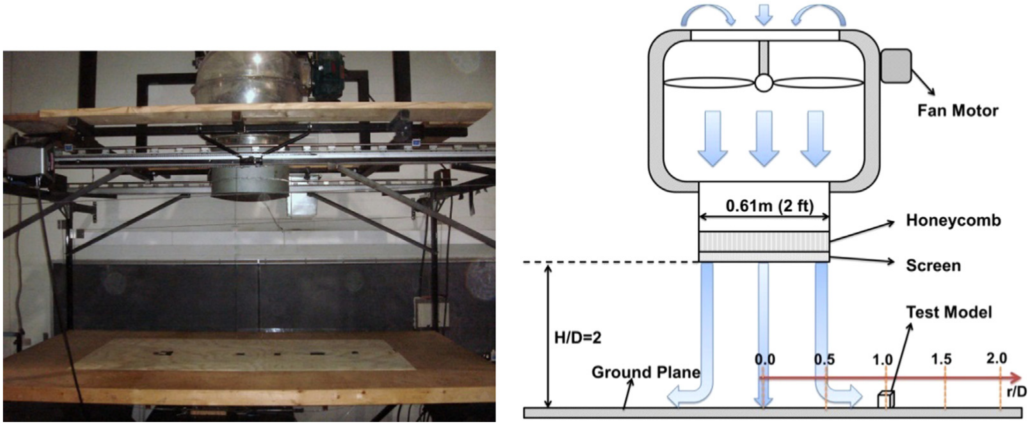

Fig. 1. Microburst simulator at Iowa State University: photo and schematic.